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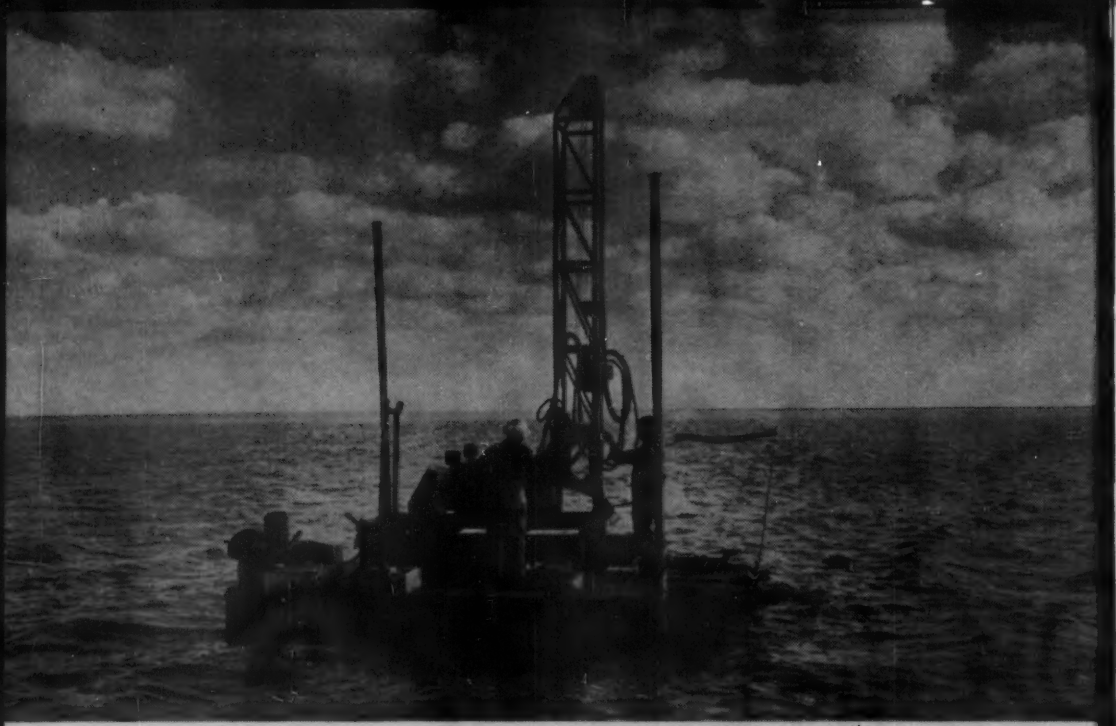

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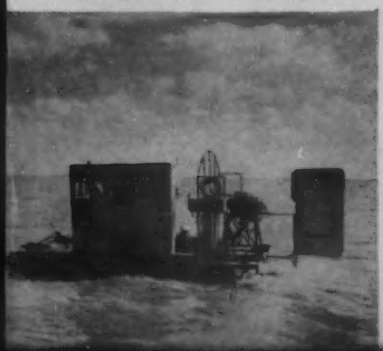

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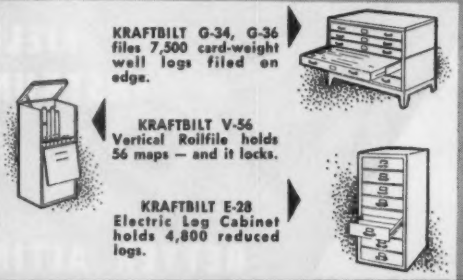

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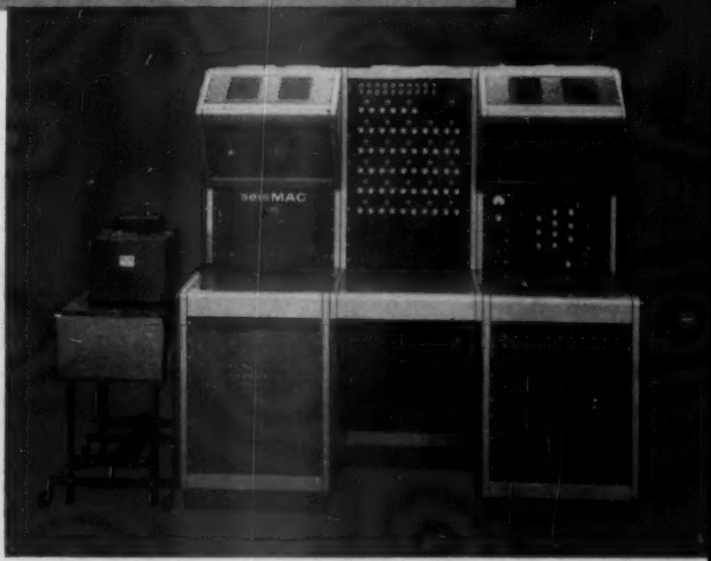

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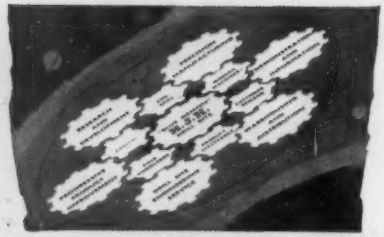

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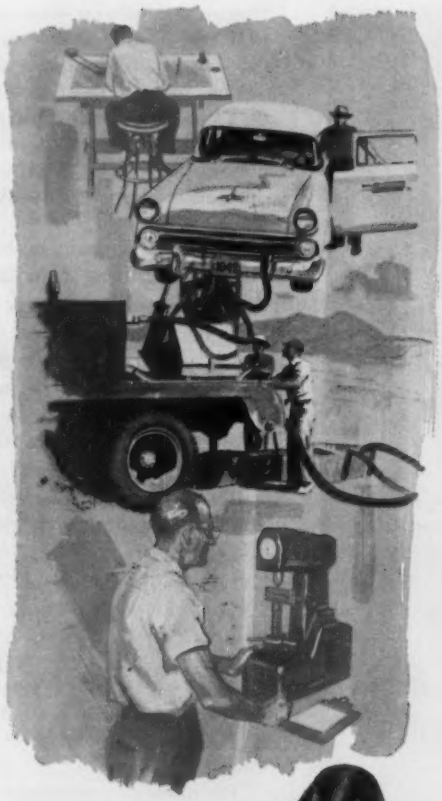

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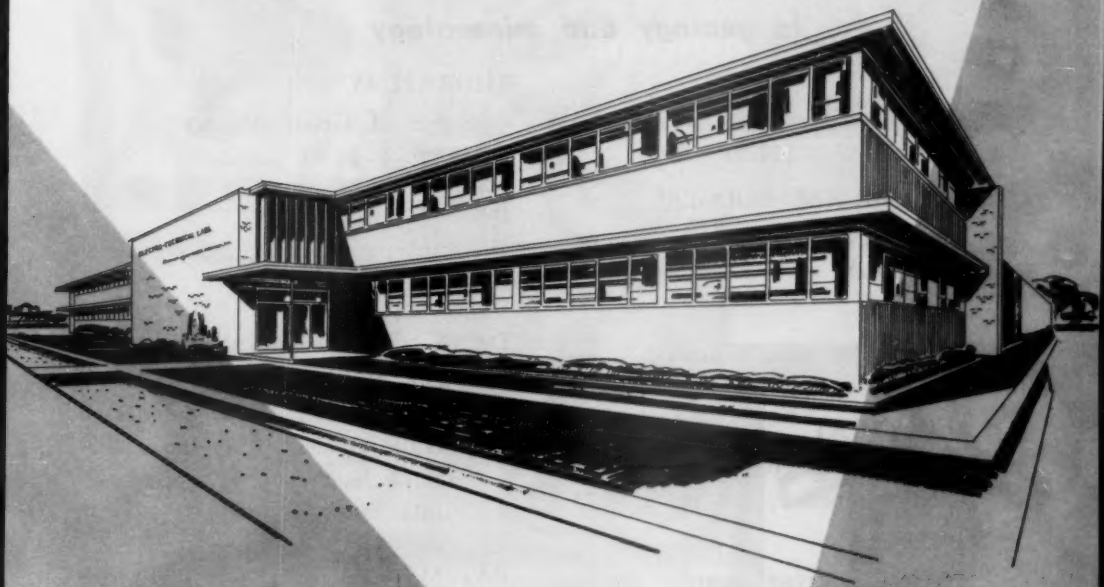

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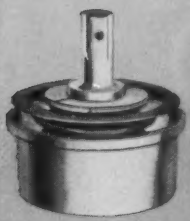

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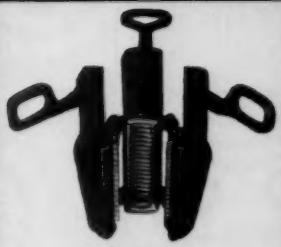

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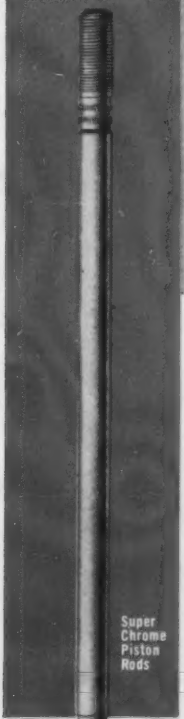

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GEOPHYSICS

VARIATION WITH DEPTH IN SHALLOW AND DEEP WATER MARINE SEDIMENTS OF POROSITY, DENSITY AND THE VELOCITIES OF COMPRESSIONAL AND SHEAR WAVES*

JOHN E. NAFE† AND CHARLES L. DRAKE†

ABSTRACT

In a study of the dependence of the velocity of compressional waves in marine sediments upon the thickness of overburden, the velocity-depth relationship in shelf sediments is shown to be distinctly different from that in deep basin sediments. The difference between the two cases may be illustrated by comparing the straight lines that best represent the data. These are

$V=1.70\,Z+1.70$ shallow water
$V=0.43\,Z+1.83$ deep water

where V is in km/sec and Z is in kilometers. Shallow and deep water are defined arbitrarily to be under 100 fathoms and over 1,500 fathoms respectively.

The observed variation of average compressional velocity in the shallow and deep water sediments, taken together with the known limited range of variation of velocity for a given porosity, yields limits in turn upon the porosity-depth dependence in the two environments. It is shown that at the same depth of overburden porosity is much greater in deep water sediments than in shallow.

A physical argument is presented to show that there is implicit in the observed narrow range of variation of velocity with porosity a simple relation between porosity and rigidity. Thus quantitative estimates of shear velocity may be made from compressional velocity alone. In this way the original data are used to place rather narrow limits on the depth variation of shear velocity, porosity, and density. A number of comparisons with observation are employed to test the conclusions at each stage of the discussion.

INTRODUCTION

Ocean sediments are at present available for study only by means of seismic investigations or by sampling with a sediment coring device. As the sediment cores rarely exceed 40 feet in length it is important to consider what information other than that on elastic wave velocities alone may be inferred from the seismic data. The possibility that reasonably accurate estimates of porosity and density variation with depth may be obtained from the compressional wave velocities is suggested by recent investigations of the relation between velocity and porosity. These studies indicate that the specific nature of the sedimentary particles has relatively little influence upon the velocity-porosity function, although such influence is demonstrably not absent. The quasi-universal nature of the velocity-porosity function is not surprising for at high porosities the elastic properties are

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† Lamont Geological Observatory.

controlled almost entirely by those of the fluid and at low porosities by those of the ultimate zero-porosity solid. The data of Wyllie, Gregory and Gardner (1956) show that a single velocity-porosity curve represents fairly well the behavior of sedimentary materials encountered in bore holes. If an almost universal velocity-porosity function exists, then porosity and density may be reliably estimated from the compressional wave velocity. In addition, shear wave velocities and elastic constants are accessible as well, for the existence of a velocity-porosity function implies a discoverable connection between the elastic constants themselves and the porosity.

In this paper there are presented first the results of a study of seismic refraction data principally from the coastal shelf of eastern North America and the adjacent ocean basins from which average velocity-depth curves for the two environments are derived. The shallow water velocity depth curve was determined from data from the East Coast of the United States north of Cape Hatteras and is not necessarily typical for all shallow water sediments. The inferences made about porosity, density, and other physical properties will not be affected by this lack of universality but will be determined by the local velocity gradient. Next is presented a discussion of the limits of uncertainty in the velocity-porosity dependence. An empirical relation between porosity and velocity is obtained that is shown to be physically plausible. From the velocity-porosity equations together with the observed deep and shallow water velocity-depth curves, the depth dependence of porosity, density, shear wave velocity, rigidity and incompressibility are derived, each with limits of uncertainty based on observed deviations from universal behavior of the velocity-porosity function.

At each stage of the discussion outlined above the conclusions are tested against observation. The average compressional velocity gradients obtained from seismic data are compared with wide angle reflection data of Officer (1955), Hill (1952) and Laughton (1954). The velocity-porosity relation is compared with data of Wyllie, Gregory and Gardner (1956), Hamilton *et al.* (1956), Laughton (1954) and with measurements at Lamont Geological Observatory by George Sutton. The depth variation of porosity is compared with the Venezuelan bore hole data of Hedberg (1956) and with artificial compaction experiments of Laughton (1954). The derived shear velocity-depth curves are used to explain the occurrence of some sound arrivals previously observed on seismic refraction records but not interpretable in terms of a simple layered structure. The shear wave velocity in deep water sediments accounts in part for the previously unexplained delay in the arrival of refracted shear waves.

The various tests against observation of the inferences drawn from the velocity-depth data and the velocity-porosity data for coastal shelf and deep water sediments show that considerable confidence may be placed in the procedure employed. It is a major conclusion of this work that, given only compressional velocity as a function of depth in sediments, the density, porosity and shear velocity may be reliably estimated.

COMPRESSIONAL WAVE VELOCITY AS A FUNCTION OF SEDIMENT THICKNESS

Over one hundred seismic refraction profiles for oceanic stations have been re-examined for the purpose of learning what might be said in general about the variation of compressional wave velocity with depth in marine sediments. Most of the stations included lie on the Continental Shelf of North America or in the adjacent ocean basins. The data were in the form of calculated velocities and thicknesses as defined in Figure 1. For all stations showing a refracted arrival associated with an interface lying within the sediment the measured velocity was plotted against the indicated thickness of overburden (excluding the water depth)

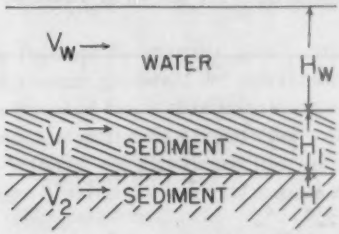

FIG. 1. Data derived from seismic refraction stations.

or, referring to Figure 1, V_2 was plotted against H_1. As would be expected, the points scatter widely as is shown in Figure 2. There is, however, a remarkable fact about the manner of distribution of points in Figure 2. Without exception they lie on the high velocity side of the curve of velocity against depth obtained by A. S. Laughton (1954) by artificially compacting a globigerina ooze. This artificial compaction curve is also shown in Figure 2.

Examination of the depths of water associated with each plotted point of Figure 2 shows that deep water stations are characterized by having lower values of velocity for a given sediment thickness than do the shallow water stations. Dividing the stations into deep and shallow, defined arbitrarily as having water depths greater than 1,500 fathoms or less than 100 fathoms respectively, and eliminating all points belonging to stations of intermediate water depth, the plotted points appear as in Figure 3. Here the upward shift of the velocity-depth curve from deep water to shallow water sediments is clearly shown. Points belonging to stations of intermediate depth scatter more or less uniformly in the gap between the concentrations of deep and shallow water points. A change of definition of "deep water station" to mean a station with a water depth greater than 2,000 fathoms increases only very slightly the concentration of deep water points near the limiting curve of Figure 2 because of the elimination of a few points from the region intermediate between the two main trends of points. The shallow and deep water cases will be discussed separately below.

It should be remarked that errors in plotted values are of several kinds. In the deep water stations the velocity in the overburden is usually assumed rather

than observed. In most cases it has been taken to be 1.8 km/sec. An error in this value will alter depths accordingly but probably not more than by 5 percent. In calculating velocities a uniform layering has been assumed. If the layers have gradients, the calculated thicknesses will be too small as has been shown by I. Lehmann (1937), and Ewing and Leet (1932). A low velocity layer would also result in low values of calculated depths. Such layers are unlikely to exist in deep water sediments but are known to be present at some shallow water locations. An estimate of the total error in the shallow water results may be made by comparing calculated depths to basement with depths determined from coastal well logs. A few such comparisons are shown in Table I.

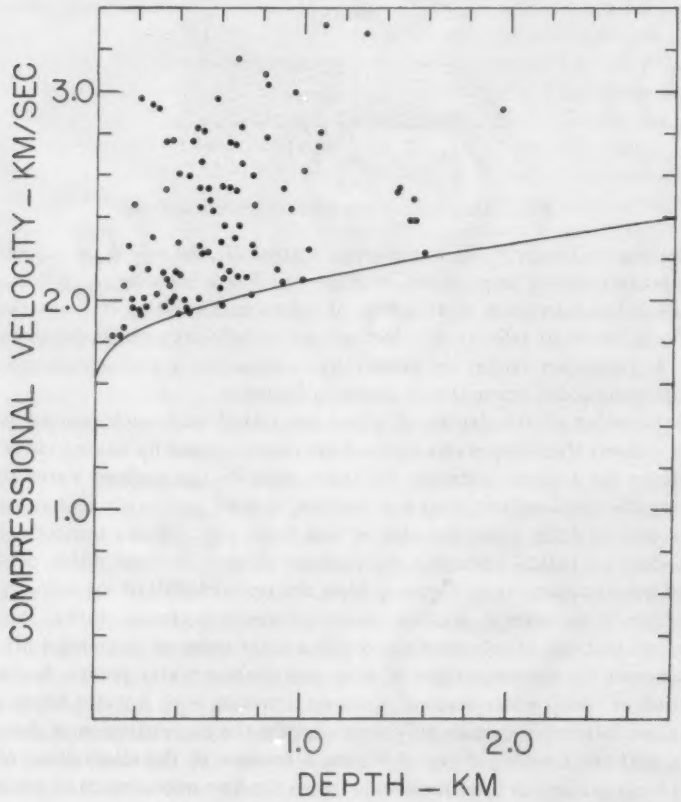

FIG. 2. Compressional wave velocities in sediments obtained from seismic refraction stations. The solid curve given by $V=0.44\sqrt{Z}+1.65$ is that obtained by A. S. Laughton (1954) for artificially compacted globigerina ooze.

TABLE I

Location	Seismic depth, ft.	Correction for regional gradient, ft.	Corrected depth, ft.	Well depth, ft.	Error %
Jackson's Mills, N. J.	−1,200	0	−1,200	−1,226	2.1*
Fort Monroe, Va.	−2,243	0	−2,243	−2,260	0.8†
Hatteras, N. C.	−9,288	−300	−9,588	−9,853	2.7‡
Matthews, Va.	−2,088	−175	−2,263	−2,297	1.5†

* Ewing, M., Wollard, G. P., and Vine, A. C. (1939).
† Ewing, M., Crary, A. P., and Rutherford, H. M. (1937).
‡ Modified from Skeels (1950).

Table I will serve to indicate the magnitude of errors in depth determination in shallow water. In deep water, gradients are smaller and low velocity layers are unlikely to occur. Thus errors of depth determination caused by these effects are probably less than in shallow water. In neither case will the errors in depth determination affect the inferred velocity-depth functions in an important way. Possible misinterpretation of refraction arrivals is more serious in the deep water

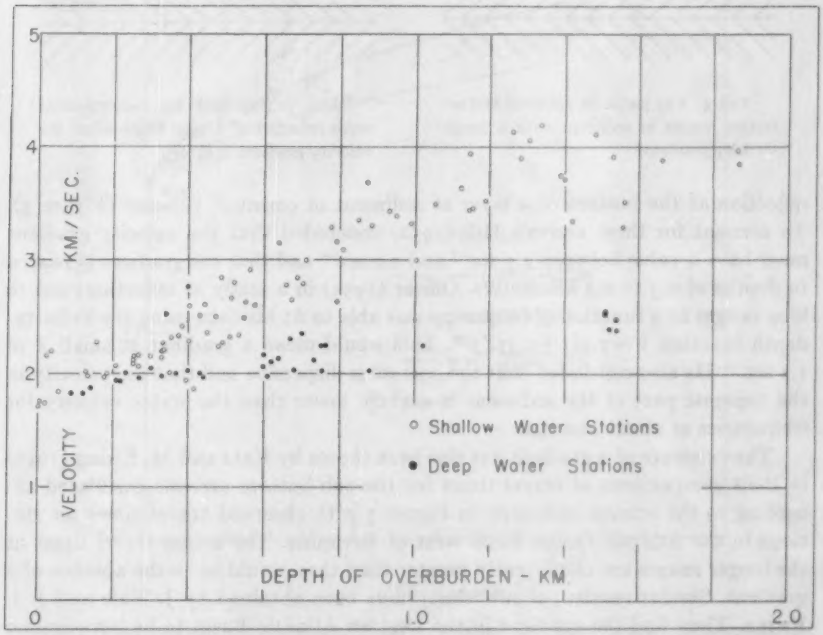

FIG. 3. Comparison of velocity-depth data for shallow (<100 fathoms) and deep water (>1,500 fathoms) seismic refraction stations. *Z* is sediment thickness (water depth excluded).

case. Overall consistency in results derived from refraction data with those from wide angle reflections is perhaps the strongest argument for the correctness of interpretation.

THE VELOCITY-DEPTH FUNCTION IN DEEP WATER SEDIMENTS

Although there are no direct measurements of velocity as a function of depth in deep water sediments, the existence of a gradient is clearly indicated by the occurrence on seismic records of sound arrivals between the first and second bottom reflections. Such sub-bottom arrivals are interpreted as having traveled by paths like *a* or *b* of Figure 4. The behavior of these arrivals at the longer ranges precludes the possibility of their having been caused by a simple sub-bottom

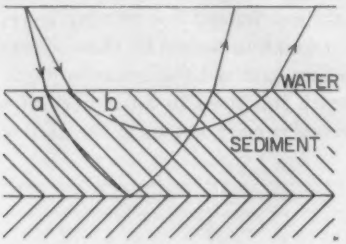

FIG. 4. Ray paths for reflected and refracted waves in sediment with a linear velocity gradient.

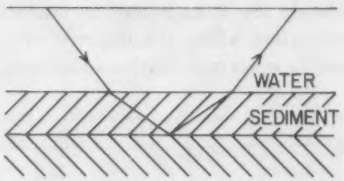

FIG. 5. Ray path for compressional wave reflected at a wide angle when the velocity gradient is zero.

reflection at the bottom of a layer of sediment of constant velocity (Figure 5). To account for these arrivals Hill (1952) concluded that the velocity gradient must have a value between 2.5 sec^{-1} and 2.0 sec^{-1} and that the gradient persisted to depths of 0.3 to 0.4 kilometers. Officer (1955) in a study of reflections out to long ranges as a function of frequency was able to fit his data using the velocity-depth function $V=1.5(1+1.37Z)^{1/2}$. This would mean a gradient at small Z of 1.1 sec^{-1}. He also concluded that the bottom is dispersive and that the velocity in the topmost part of the sediment is slightly lower than the water velocity for frequencies of about 100 cps.

The existence of a gradient has also been shown by Katz and M. Ewing (1956) in their comparisons of travel times for the sub-bottom arrivals calculated according to the scheme indicated in Figure 5 with observed travel times for stations in the Atlantic Ocean Basin west of Bermuda. The actual travel times at the longer ranges are consistently greater than they would be in the absence of a gradient. Similar results (unpublished) have been obtained by J. Nafe and J. I. Ewing. They find the gradient in the western Atlantic Basin to be between 1.0 and 2.0 sec^{-1}.

A. S. Laughton (1954) investigated in the laboratory the velocity dependence

upon pressure for artificially compacted globigerina ooze. From measurements of density as well he obtained an experimental curve of compressional wave velocity as a function of depth. He reported the velocity-depth function to be represented by the parabola

$$V = 0.44\sqrt{Z} + 1.65 \qquad (1)$$

where V is measured in km/sec and Z in kilometers. The mean gradient to a depth of 0.3 km was found to be 0.8 sec^{-1}.

In Figure 6 there are shown the velocity-depth curves obtained by Hill, Officer and Laughton compared with the present deep water data. The curves of Officer and Hill are both obtained by the best choice of gradient to fit the observed sub-bottom arrivals. Their gradients of 2.0 sec^{-1} and 1.1 sec^{-1} respectively represent appropriate average gradients over perhaps the first 0.3 km of sediment. Although Officer's curve is a parabola it has very little curvature in the region of

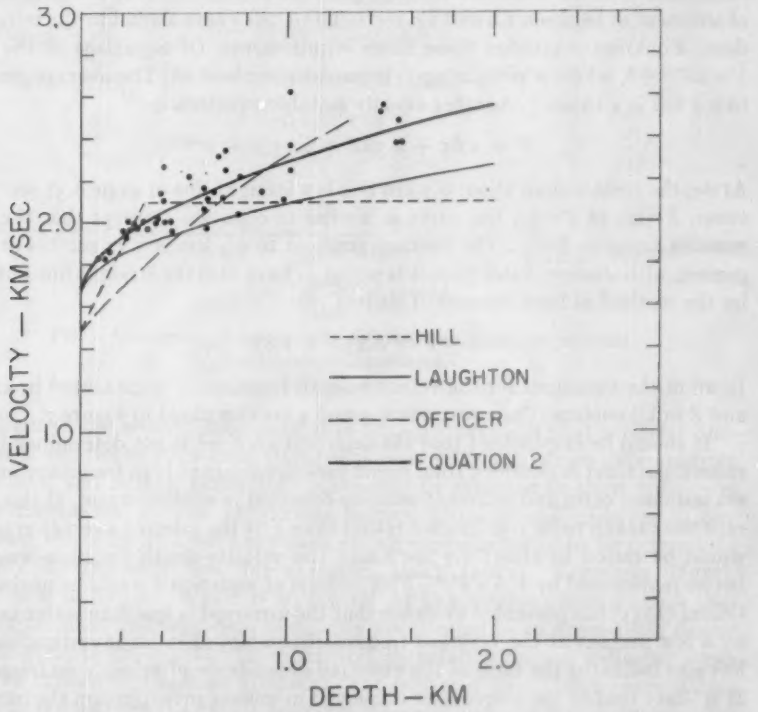

FIG. 6. Compressional velocity-depth dependence from deep water seismic data compared with results obtained from wide angle reflections (or refractions) of Hill and Officer and with Laughton's artificial compaction data.

its applicability and is a close approximation to a linear gradient. It was selected to fit the wide angle reflection data at very low frequencies.

The remaining curve shown on Figure 6 is of the same form as Laughton's but with one modified constant.

$$V = 0.64\sqrt{Z} + 1.65. \tag{2}$$

It will be observed that this fits the data well although there is a suggestion that it gives too high a value for velocity at depths less than 0.2 km.

In fitting a curve to the deep water data, three facts must be kept in mind. First, the observed values of velocity at the water sediment interface are in the neighborhood of 1.65 km/sec on the average though they may vary from perhaps 1.67 km/sec to 1.47 km/sec. Such observations have been reported by Shumway (1956), Laughton (1954) and have been made at Lamont Geological Observatory (unpublished) by Sutton, Berckhemer and Nafe. Second, the curve should be consistent with the observed average gradient of velocity over the first 0.3 km of sediment of between 1.0 and 2.0 sec^{-1}. Third, the curve should fit the refraction data. Equation 2 satisfies these three requirements. Of equations of the form $V = aZ^{1/n} + b$, where n is an integer, it provides the best fit. The average gradient to 0.3 km is 1.16 sec^{-1}. Another equally suitable equation is

$$V = 1.65 + 0.38Z + 0.25(1 - e^{-10Z}). \tag{3}$$

At depths greater than about 0.3 km this is a straight line of slope 0.38 sec^{-1}. Between $Z = 0$ and $Z = 0.3$ the curve is similar to equation 2 except that the slope remains finite at $Z = 0$. The average gradient to 0.3 km is 1.21 sec^{-1}. For comparison with shallow water data it is useful to have also the straight line obtained by the method of least squares. This is

$$V = 0.43Z + 1.83. \tag{4}$$

In all of the equations for the velocity-depth function, V is measured in km/sec and Z in kilometers. The equations 2, 3 and 4 are compared in Figure 7.

It should be emphasized that the intercept on $Z = 0$ is not determined by the seismic data but is obtained from direct measurements at high frequency on deep sea sediment cores and sediment samples collected in shallow water. If this intercept were taken to be 1.50 km/sec rather than 1.65 the inferred average gradients would be raised to about 1.7 sec^{-1} and the velocity-depth function would be better represented by $V = a'Z^{1/3} + b'$. The form of equation 2 would be unchanged. Officer (1955) has presented evidence that the intercept is less than water velocity by a few percent at the very low frequencies employed in his investigations. He has also indicated the form of the expected dependence of velocity on frequency. It is likely that at the frequencies employed in seismic investigation the intercept of velocity upon $Z = 0$ is lower than the value 1.65 determined at high frequency and that the average gradient over 0.3 km is larger than 1.2 sec^{-1}.

The velocity-depth curve of Laughton shown in Figure 2 appears to be a

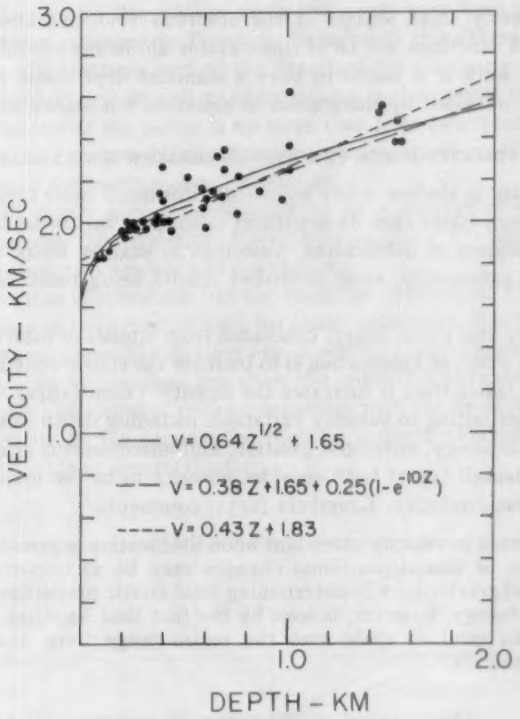

FIG. 7. Comparison of equations representing deep water compressional velocity-depth dependence.

lower limit to the seismic data. Now it is certainly probable that artificial compaction of sediments other than globigerina ooze will yield curves different from Laughton's, and in fact, globigerina oozes may be expected to show differences among themselves because of various factors, physical and chemical. Compressional velocities at $Z=0$ have been shown experimentally to be determined primarily by porosity. See, for example, Urick (1947), Krumbein (1951), Hamilton *et al.* (1956), Wyllie *et al.* (1956). At compaction pressures such that the bulk modulus and coefficient of rigidity are affected to an appreciable degree through grain-to-grain contacts, differences in velocity among sediment types would be expected to become apparent. The fact that Laughton's curve differs as little as it does from the data is probably a demonstration not that the velocity-depth curve for globigerina ooze is a real lower limit but rather that (a) differences in the velocity-depth curve among deep water sediment types are small, and (b) lithification is inhibited in deep water.

The relatively small scatter of the observed velocities about the derived velocity-depth functions will be of considerable aid in seismic reflection work at sea. For this work it is useful to have a standard depth-time curve available. Such a curve obtained by integration of equation 2 is shown in Figure 8.

THE VELOCITY-DEPTH FUNCTION IN SHALLOW WATER SEDIMENTS

The velocity in shallow water sediments rises much more rapidly with depth than in the deep water case. It is natural to suppose this to be the consequence of different degrees of lithification. Velocities in shallow water sediments have been studied extensively, most published results being based on well velocity studies.

Weatherby and Faust (1935) concluded from studies of interval velocities in wells that the effect of lithification is to increase the elastic constants (and hence the velocity) faster than it increases the density. Olson (1941) listed a number of factors contributing to velocity variations including depth of burial, location, geologic age, lithology, structural position, and miscellaneous local factors. West (1950) and Haskell (1941) both consider porosity to be the major factor in determining seismic velocity. Krumbein (1951) comments:

"The increase in velocity attendant upon lithification suggests that the depth of overburden or post-depositional changes may be as important as original sedimentary characteristics in determining final elastic properties. The influence of original lithology, however, is seen by the fact that lime has higher average velocities than sand or shale over the entire range from unconsolidated to lithified equivalents."

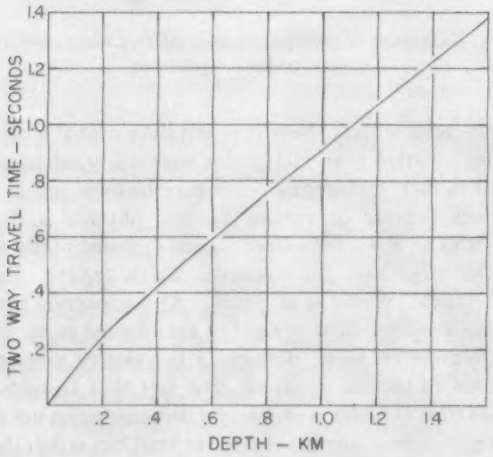

FIG. 8. Average two-way travel time as a function of sediment thickness for deep water sediments.

Seismic velocities for the shallow water sediments have been plotted against depth of overlying sediment in Figure 9. Included in this diagram are interval velocities from the Hatteras well of the Standard Oil Company of New Jersey as given by Skeels (1950) as well as observations in the coastal plain sediments on land. The scatter of the points is no more than is to be expected considering the lithological and geographical differences, the reconnaissance nature of the observations, and the method of interpretation.

The data of Figure 9 may be represented by a number of equations with about equal success. The equation $V=1.70+4.30\ (1-e^{-Z/2})$ fits the data well and varies between 1.70 km/sec and 6.00 km/sec.

The lower value is reasonable for the mean for material at the surface, and the upper is close to the expected limit for clastic sediments. Two other velocity-depth functions are given; the straight line, $V=1.70\ (1.00+Z)$, and the parabola, $V^2=9Z+2.56$. The former does not show the curvature indicated by the data but is included for purposes of ready comparison with the deep water data. The parabola is similar to the exponential form to a depth of about 1.8 km, but diverges considerably at greater depths.

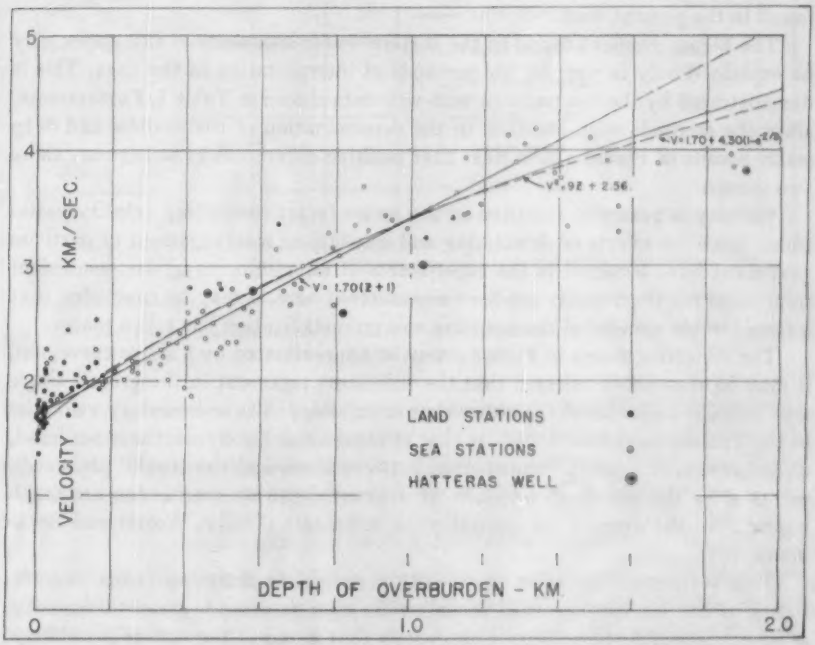

FIG. 9. Compressional velocity-depth dependence in shallow water sediments. Comparison of various equations.

The increase of velocity with depth measured here is somewhat greater than that reported from well velocity measurements by others. Hafner (1940) in California found a linear gradient, $V = V_0 + kZ$, with V_0 varying between 1.70 and 2.50 km/sec, and k between 0.4 and 0.6 sec^{-1}. The sediments involved in this work were sandstones, shales and coarser clastics, without large volumes of chemical precipitates. Haskell (1941) found a mean value for the gradient in Tertiary shales of the San Joaquin Valley, California, of 0.464 sec^{-1}, and presented evidence to show that 78 percent of the gradient was due to the pressure of the overburden. He attributes the remainder to an increase of cementation in the older beds. Weatherby and Faust (1935) studied wells in the Mid-Continent and Gulf Coast areas. Their results show gradients of 0.69 sec^{-1} for Pleistocene-Oligocene, 1.22 sec^{-1} for Eocene, 1.30 sec^{-1} for Cretaceous, and 1.13 sec^{-1} for Permian rocks. Faust (1951) extended this work to include a time element in the empirical formula, $V = 125.3(ZT)^{1/6}$ where V is velocity in ft/sec, Z the depth in feet, and T the age in years. West (1950) fitted data from clastic sediments to an equation of the form $V = V_0(1 + cZ/V_0^4)$, where $c = 3.3$ sec^{-1}. Substituting 1.70 km/sec for V_0, this reduces to $V = 1.70 + 0.67Z$. His results, as well as those mentioned earlier, are plotted in Figure 10 together with the approximate curve found in the present work.

The higher gradient found in the shallow water sediments of this paper may be explained only in part by the methods of interpretation of the data. This is demonstrated by the comparisons with well data shown in Table I. Furthermore, since the methods were identical in the determination of the shallow and deep water results of Figure 3 it is clear that positive differences exist between these two groups.

Porosity is generally accepted as the major factor controlling velocity variations. Since the effects of dewatering and mechanical rearrangement of particles that must have occurred in the experiments of Laughton (1954) are insufficient to account for the velocity gradient encountered here, it may be concluded that a considerable amount of cementation and recrystallization has taken place.

The velocities shown in Figure 9 may be approximated by a single curve, and it may be reasonably inferred that the sediments represent in the gross a single unit without major breaks in either time or lithology. The sedimentary velocities in the Triassic fault basins such as that of the Bay of Fundy, on the other hand, do indicate that a break has occurred between them and the coastal plain sediments since the observed velocities at a given depth of overburden are much higher than the average for coastal plain sediments (Drake, Worzel and Beckmann, 1954).

This systematic variation in velocity is an aid in detecting errors or oversights in the interpretation of seismic refraction results. A great thickness of sediment in which the velocity is uniformly that found at the surface is unlikely. The refraction results presented by Skeels (1950) fall into this category. The thickness of sediment given indicates that higher velocities should be present.

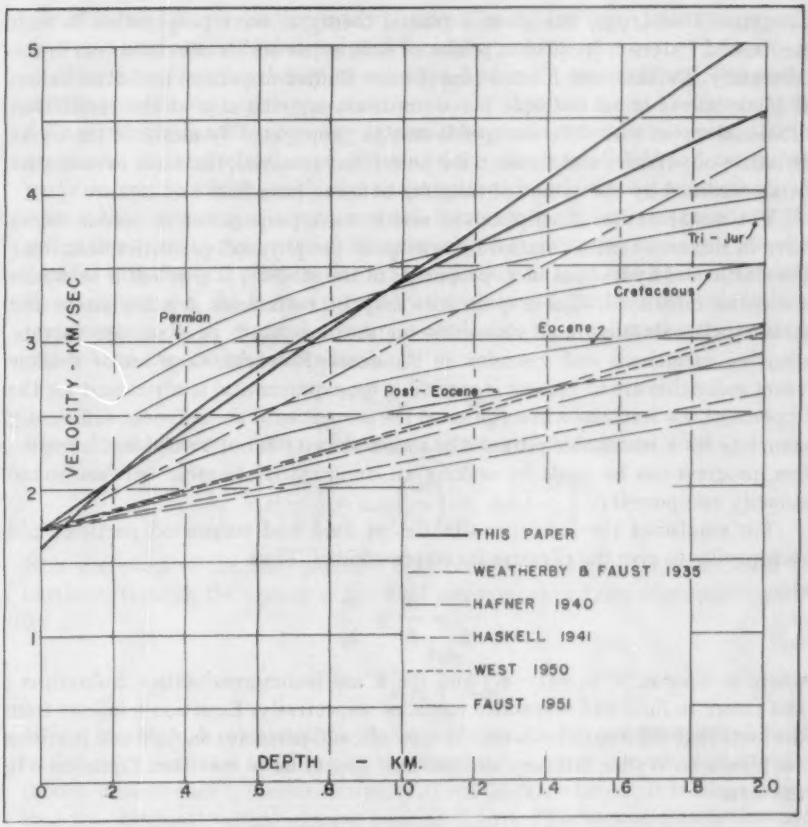

FIG. 10. Comparison of average shallow water compressional velocity-depth dependence with results of others.

His data may be reinterpretated by inserting an intermediate layer. The presence of such an intermediate layer is suggested by "secondary" arrivals on his travel-time curves. The resulting basement depths are then in good agreement with the well data and the need for a "high-speed limestone layer" is eliminated.

THE DEPENDENCE OF VELOCITY UPON POROSITY

The velocities of elastic waves in porous media are related to the properties of the medium in a complex manner. Not only are waves of dilation and rotation possible but there may be two dilational waves having different velocities dependent upon properties of the fluid, the lattice and the coupling. Furthermore, compacted porous media may be anisotropic as has been demonstrated by A. S.

Laughton. Biot (1956) has given a general theory of wave propagation in such media, and Paterson (1956) has produced both types of dilatational waves in the laboratory. Zwikker and Kosten (1949) have studied dispersion and attenuation of plane waves in an isotropic porous medium arriving also at the result that dilational waves with different speeds may be propagated by means of the frame or lattice of particles and through the pore-filling material, the wave in each case being modified by the extent of coupling between pore filler and lattice.

The mathematical descriptions of elastic wave propagation in porous media have in common that a detailed knowledge of the physical quantities describing the elastic and hydrodynamical properties of the medium is required if velocities are to be calculated. These quantities may be coefficients relating stress and strain, permeabilities, and viscosities on the one hand, or structure factors, coupling coefficients and viscosity on the other. However, deep sea or shallow water sediments are at present inaccessible for experimental study except for the uppermost few feet, and a description of the properties of the sediment sufficiently complete for a reasonable estimate of sound velocity is not available. Nevertheless, progress can be made by seeking an empirical relationship between sound velocity and porosity.

For emulsions the incompressibilities of fluid and suspended particles add reciprocally to give the effective incompressibility. Thus

$$\frac{1}{k} = \frac{\phi_1}{k_1} + \frac{\phi_2}{k_2} \tag{6}$$

where ϕ_1 = porosity, $\phi_2 = (1-\phi_1)$ and the k are incompressibilities. Subscripts $_1$ and $_2$ refer to fluid and suspended particles respectively. Equation 6 follows from the facts that differential volume changes add and pressures on fluid and particles are identical. Wyllie, Gregory and Gardner (1956) have rewritten Equation 6 in the form

$$\frac{(1+q)}{\rho V^2} = \frac{\phi_1}{\rho_1 V_1^2} + \frac{\phi_2(1+q_2)}{\rho_2 V_2^2} \tag{7}$$

where $\rho = \rho_1\phi_1 + \rho_2\phi_2$ and $q = 4/3\ \mu/k$ with μ = rigidity. Equation 7 with $q = q_2 = 0$ has been used by Urick (1947) to determine compressibilities of suspended particles from sound velocity measurement and by Wyllie, Gregory and Gardner with $q_2 = 0.6$ to calculate sound velocities of aggregates of glass beads in fluids. They have demonstrated also the validity of the equation

$$\frac{1}{V} = \frac{\phi_1}{V_1} + \frac{\phi_2}{V_2} \tag{8}$$

for transmission of sound through a pile of alternating aluminum and lucite disks in a direction along the axis of the pile. According to Wyllie, Gregory and Gardner (1956) the time average velocity of equation 8 represents fairly well the observed

porosities and corresponding interval velocities in bore holes, although a better fit would be given if it predicted slightly higher velocities.

The time average velocity of equation 8 at low porosities, and equation 7, at high porosities are fair approximations to the observed facts. Another equation fitting both high and low porosity data may be obtained by the following physical argument. In the derivation of equation 6 the compressed fluid and compressed particles are, in effect, considered to be springs in series with each other. The reason that equation 7 fails to give the correct velocity at low porosity is that under compression the material behaves as if another spring had been placed in parallel with the first combination. It is necessary to take into account the additional stiffening of the system caused by the lattice of particles through grain-to-grain contacts. If an external pressure is applied to the total system the pressures rather than the volumes will add. Thus

$$P = \phi_1 P_f + \phi_2 P_s$$

where f and s refer to fluid and lattice. In terms of incompressibilities

$$k\left(\frac{dv}{v}\right) = \phi_1 k_f \left(\frac{dv}{v}\right)_f + \phi_2 k_s \left(\frac{dv}{v}\right)_s. \tag{9}$$

Now the effect of the fluid pressure is to compress the entire system, fluid and particles, through the agency of the fluid pressure; thus k_f may be approximated by

$$k_f = \frac{k_1 k_2}{k_1\phi_2 + k_2\phi_1}$$

or just equation 6 rewritten. No definite properties will yet be ascribed to the lattice other than that of occupying the entire volume and possessing an effective, though undetermined, incompressibility. Thus $(dv/v)_s = (dv/v)$. It is now assumed that the fractional volume change associated with P_f is approximately the same as that for the entire volume or

$$\frac{dv}{v} = \left(\frac{dv}{v}\right)_f = \left(\frac{dv}{v}\right)_s$$

and there results

$$k = \phi_1 \frac{k_1 k_2}{k_1\phi_2 + k_2\phi_1} + \phi_2 k_s. \tag{10}$$

It will be assumed in addition that

$$k_s = (\phi_2)^{n-1} k_2 \quad \text{and} \quad \mu = \mu_s = \phi_2{}^n \mu_2$$

where the subscript 2 refers as before to the solid particles. It is thereby insured that at porosities 0 and 1, μ and k have the proper limiting values. The exponent

n will be determined by comparison with experiment and observation. The exponents $n-1$ and n are assumed for k_s and μ_s respectively to insure that the ratio μ/k will be approximately 0.6 at porosities that are small but considerably larger than zero. By adding $4/3\mu_s$ to both sides of equation 10 and dividing by appropriate densities there results

$$V^2 = \phi_1 V_W^2 + \frac{\rho_2}{\rho}\phi_2^n V_2^2 \tag{11}$$

where V_W is the velocity given by equation 7 with $q=0$.

Comparison of equation 11 with experimental data shows that for values $n=4$ or 5 a fairly good representation of the facts both at high and low porosity is obtained. Equation 11 does, however, give values of velocity that are slightly too low at high porosity. This cannot be improved by different choice of n. A slight modification of equation 11 results in a velocity equation that appears to be quite satisfactory. This is

$$V^2 = \phi_1 V_W^2\left(1 + \frac{\rho_1}{\rho}\phi_2\right) + \frac{\rho_2}{\rho}\phi_2^n V_2^2. \tag{12}$$

The maximum contribution of the added term occurs at approximately $\phi_1=0.8$ and adds about seven percent to the value of velocity there.

In Figure 11 the velocity calculated from equation 12 with $V_2=6.0$ km/sec is compared with velocities given by equation 7 with $q=0$ and equation 8. On the same figure are shown the experimental average curve of Wyllie, Gregory and Gardner which best fits their bore hole data, the artificial compaction results of Laughton (1954), and data obtained by George Sutton from a wide selection of deep sea sediment cores. Most of the observations lie between the $n=4$ and $n=5$ curves of equation 12. It cannot be said that there exists a single velocity-porosity curve. The specific nature of the sedimentary particles and their past history undoubtedly each determine to some extent the velocity at a given porosity. It is important to recognize, however, that the major factor influencing the velocity is porosity alone and that while they do not represent the outside limits of possible variation, the $n=4$ and $n=5$ curves contain between them most of the observed cases.

In Table II there are compared the predictions of equations 7, 8 and 12 for $V_2=6.0$ km/sec and $\rho_2=2.65$ gm/cm^3. There are also tabulated a few experimental observations.

A comparison with experiment may also be made of the prediction for shear modulus and incompressibility according to $\mu=\phi_2^n\mu_2$ and equation 10. In Table III values of μ calculated using $\mu_2=3.18\times10^{11}$ c.g.s. and $n=5$ are compared with observations of A. S. Laughton (private communication) at three different pressures. The value of μ_2 is consistent with $V_2=6.0$ km/sec and $\mu_2/k_2=0.6$. In this comparison $n=5$ fits Laughton's porosity data better than $n=4$, as is shown in

TABLE II
VELOCITY—km/sec

Porosity	Velocity of emulsion equ. 7	Time average velocity equ. 8	Compaction velocity $n=4$ equ. 12	Compaction velocity $n=5$ equ. 12	Observed velocity (average cores)*	Bore hole velocities†	Artificial compaction‡
1.0	1.53	1.53	1.53	1.53			
0.9	1.50	1.65	1.49	1.49			
0.8	1.49	1.79	1.48	1.45	1.48		
0.7	1.50	1.97	1.56	1.43	1.50		
0.6	1.54	2.18	1.80	1.54	1.65		1.82
0.5	1.60	2.43	2.24	1.82			2.10
0.4	1.70	2.76	2.79	2.30			2.38
0.3	1.86	3.19	3.40	2.92		3.42	2.83
0.2	2.22	3.79	4.24	3.83		4.23	
0.1	2.72	4.63	5.13	4.88		5.10	
0	4.58	6.00	6.00	6.00		6.00	

* George Sutton, Lamont Observatory, Experimental Averages.
† Wyllie, Gregory and Gardner, Experimental Averages.
‡ A. S. Laughton, Globigerina Ooze.

Figure 11. The calculated values of μ in Table III are too high and those for k are too low. It would appear from the plotted values of Laughton's data shown in Figure 10 that the cause of this discrepancy is more likely to be found in the measurements of porosity in the high pressure range than in the choice of exponent for ϕ_2.

TABLE III
COMPARISON OF CALCULATED AND OBSERVED ELASTIC CONSTANTS

Pressure, kg/cm^2*	Velocity (Observed) km/sec*	Density, gm/cm^3*	ϕ_2*	μ (Calculated) $\times 10^{11}$	μ (Observed) $\times 10^{11}$*	κ (Calculated) $\times 10^{11}$	κ (Observed) $\times 10^{11}$*
512	2.68	2.14	0.68	0.46	0.31	1.02	1.13
768	2.89	2.22	0.72	0.60	0.45	1.05	1.25
1,024	3.06	2.26	0.74	0.70	0.56	1.19	1.38

* A. S. Laughton (1954).

VARIATION OF POROSITY AND DENSITY WITH DEPTH

The compressional velocity-porosity functions given by equation 12 with $n=4$ and $n=5$ contain between them most of the observed points in the high porosity range and they are in reasonable agreement with the experimental average curve of Wyllie, Gregory and Gardner at low porosity. Although the two curves do not represent the outside limits of possible porosities at a given velocity they do provide a fairly typical spread of porosity values. When used together with the velocity-depth curves for deep and shallow water there is obtained for each case a porosity-depth curve. In Figure 12 the porosity-depth curves for deep and shallow water are compared. The dashed curve of the figure

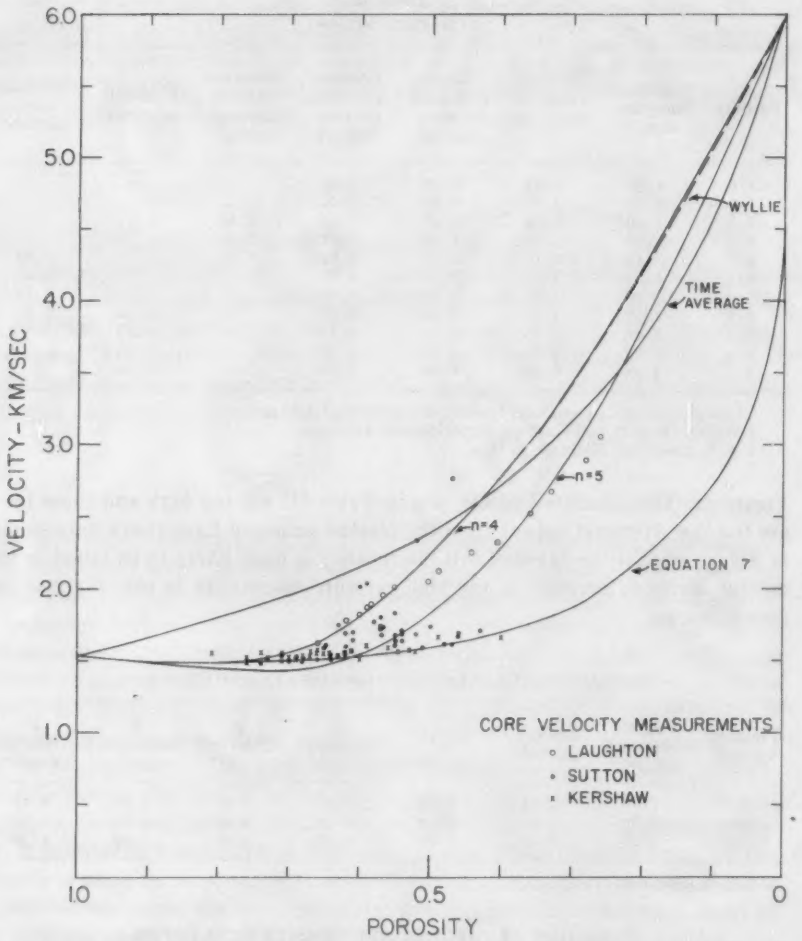

FIG. 11. Porosity-compressional wave velocity dependence. The points of Sutton and Kershaw were made on uncompacted sediment core materials. Laughton's data were obtained with artificially compacted globigerina ooze. The dashed curve is the experimental average of Wyllie, Gregory and Gardner (1956) from bore hole data.

is the porosity-depth curve obtained from the void ratio-compaction pressure measurements of A. S. Laughton (private communication) and from Laughton's pressure-depth relation (1954). The dotted curve is the porosity-depth curve obtained by Hedberg (1936) from wells in Venezuela and Kansas. If Hedberg's curve is used with the velocity-porosity relations to obtain compressional

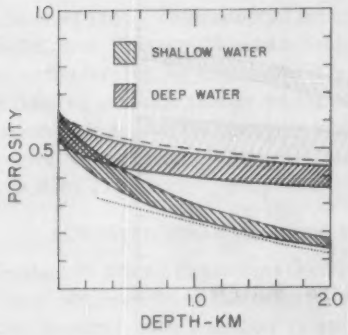

FIG. 12

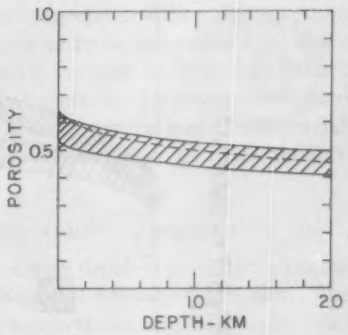

FIG. 13

FIG. 12. Porosity-depth dependence for average deep and shallow water sediments. The dashed curve was obtained from Laughton's artificial compaction data. The dotted curve is a combination of the Venezuelan and Kansan bore hole data of Hedberg (1936).

FIG. 13. Porosity-depth dependence for artificially compacted sediment. Probable porosity range (shaded) derived from velocity data compared with measured porosities (dashed line). Velocity and porosity measurements are those of Laughton for artificially compacted globigerina ooze.

velocities, these fall within the range of velocities contributing to the shallow water average curve. In Figure 13 the porosity-depth curve inferred from the velocity measurements of Laughton (1954) is compared with that obtained from his void ratio-compaction pressure data.

The variation of density with depth in deep and shallow water is shown in Figure 14. These curves were obtained from the porosity-depth curves together with the linear relation between density and porosity

$$\rho = \phi_1\rho_1 + \phi_2\rho_2,$$

with $\rho_1 = 1.04$ gm/cm³ and $\rho_2 = 2.65$ gm/cm³. It is interesting that despite the dependence of bulk density upon the particle grain density, the data in the "Handbook of Physical Constants" (1942) indicates that soil, sand, sandstone, limestone, clay and shale all fall on nearly the same straight line with a value of ρ_2 nearly 2.68 gm/cm³. This is illustrated in Figure 15. There are also shown in that figure data of Hamilton (1956) and Sutton on ocean sediment densities. These too obey very well the same linear density-porosity dependence. All the points plotted in the various sections of the figure are compared with the same straight line

$$\rho = 1.00\phi_1 + 2.68\phi_2.$$

The range of densities in deep water indicated in Figure 14 shows the maximum density at two kilometers to be not more than about 2.1 gm/cm³. Worzel

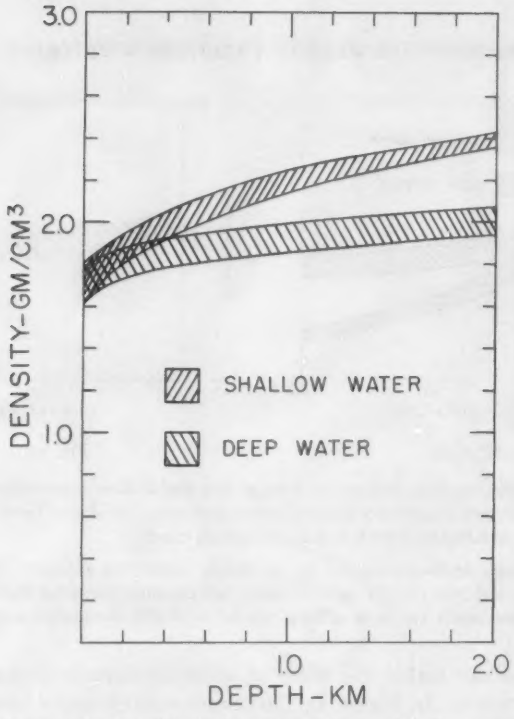

FIG. 14. Variation of density with depth in average deep and shallow water sediments.

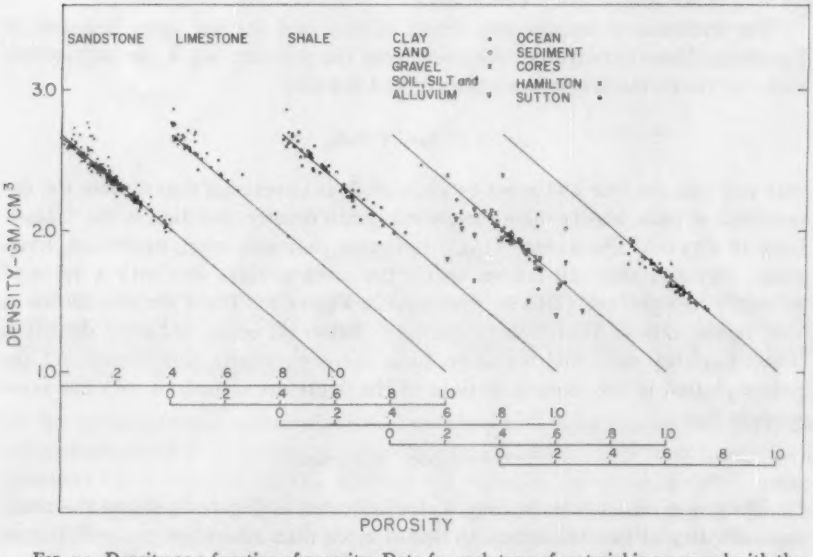

FIG. 15. Density as a function of porosity. Data for each type of material is compared with the same line $\rho = 1.00\phi_1 + 2.68\phi_2$ where $\phi_1 =$ porosity and $\phi_2 = 1 + \phi_1$. All data except that on ocean sediment cores are from the "Handbook of Physical Constants," Geological Society of America, Special Paper No. 36, edited by Birch (Chairman), Schairer and Spicer.

and Shurbet (1955) have adopted for gravity computations the value 2.3 gm/cm³ for sediments. This would appear from Figure 14 to be appropriate for shallow water sediments but for deep water it is probably too high. As Worzel and Shurbet have pointed out, this change would not affect their standard oceanic column to an appreciable degree. On the other hand, this density might make an appreciable difference where there are large accumulations of sediment as there are in the Puerto Rico Trench.

ESTIMATED SHEAR VELOCITY, RIGIDITY AND INCOMPRESSIBILITY

In the two preceding sections the variation with depth of porosity and density has been obtained from the original compressional velocity-depth data. These results, together with equation 12 and the assumptions that lead to it, will be used to find the shear velocity and the elastic constants.

It is quite true, of course, that sediments may be anisotropic, that *SH* and *SV* phases may have different speeds, that grain particle types and geometries may influence the elastic properties and that hysteresis effects do occur. Despite these known complexities it would appear from the results of the last two sections that the principal effects of compaction on elastic properties may be described empirically in terms of porosity alone.

Beginning then with the velocity-depth curves for deep and shallow water, there corresponds to each velocity a value of ϕ_2 from equation 12 for $n=4$ and $n=5$. Rigidity may be calculated from $\mu=\phi_2{}^n\mu_2$ and the density from $\rho=\phi_1\rho_1+\phi_2\rho_2$. In these calculations μ_2 is taken to be 3.2×10^{11} c.g.s., and ρ_2 to be 2.65 gm/cm³. Again the $n=4$ and $n=5$ curves are considered to contain between them most of the observed velocity-porosity data. Then from $V_s=\sqrt{\mu/\rho}$ the shear velocities are obtained. The results, plotted as a function of depth, are shown in Figure 16. It should be noted especially that for a given compressional velocity, ϕ_2 from $n=4$ is less than the corresponding ϕ_2 from $n=5$. Consequently the two values of μ obtained from the two exponents are quite close together. Moreover the densities also differ in the two cases. These differences occur in such a way that the resulting values of V_s are within two percent of each other over the entire range of velocities encountered in deep and shallow water. In Figure 16, therefore, no distinction is made between the assumptions $n=4$ and $n=5$.

The rigidities together with values of incompressibility derived from

$$k/\mu = (V_p/V_s)^2 - 4/3$$

are plotted as functions of depth in Figure 17. Here again no distinction is made between results for $n=4$ and $n=5$. In this case the differences amount to about five percent, but this is certainly less than errors likely to result from other causes such as anisotropy.

Similarly μ/k and Poisson's ratio may be found. The results are presented as functions of porosity rather than depth. These curves are shown in Figure 18.

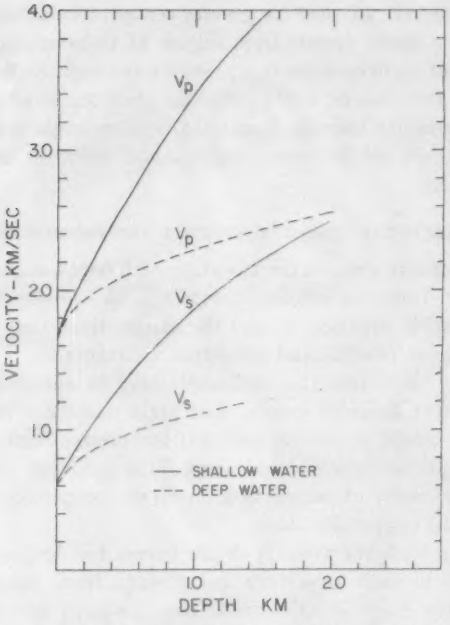

FIG. 16. Variation with depth of compressional wave velocity (V_P) and shear wave velocity (V_S) for shallow and deep water sediments. The compressional velocities are average curves representing the seismic refraction data, and the shear velocities are derived from the compressional velocities by means of the velocity-porosity relation.

The spread between values obtained for $n=4$ and $n=5$ is illustrated by the widths of the plotted curves. In connection with Figure 18 it should be noted that almost the same results as those presented here for shear velocity and elastic constants would have been obtained with the very simple assumption that $\mu/k=0.6\phi_2$. This relation is a straight line joining $\mu/k=0.6$ at zero porosity to $\mu/k=0$ at a porosity of unity. Although μ/k would differ at times by as much as twenty percent from the results of this section, the shear velocity would differ by only about ten percent. This assumption is certainly in fair accord with all the facts against which those of Section V are tested and it permits the simple estimation of shear velocity from compressional velocity and porosity alone.

OBSERVATION OF REFRACTED SHEAR WAVES

During the summer of 1956 a party from Lamont Geological Observatory aboard the Research Vessel THETA in company with the vessel PATROLLERO V-17 of the Spanish navy shot six refraction profiles on the seaward extension of the Guadalquiver Basin on the southeast coast of Spain. The stations were

characterized by exceedingly weak basement arrivals. The travel time plot of compressional waves arriving through the sediments reveals a velocity-depth variation which is in remarkably good agreement with that of the Continental Shelf of eastern North America shown in Figure 16. In addition to these compressional waves, there were observed large amplitude arrivals that plotted nearly on a straight line. These could not be interpreted by reason of the high zero range

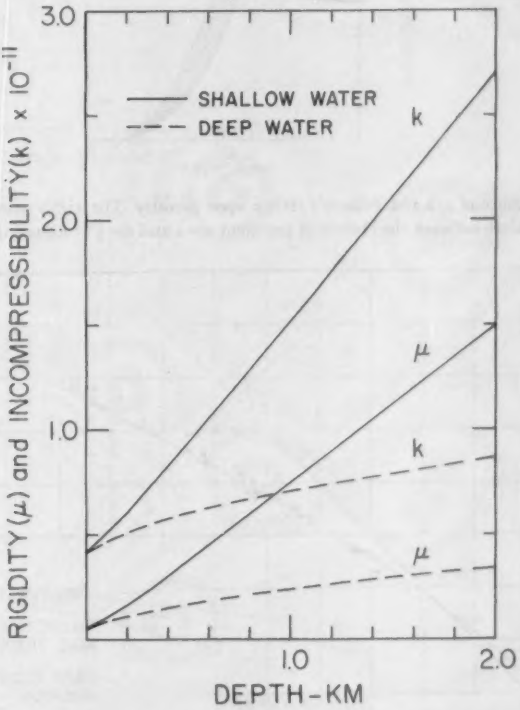

FIG. 17. Variation of incompressibility (k) and rigidity (μ) with depth derived from the average compressional velocity-depth data and the velocity-porosity relation.

intercept as shear in the basement. Comparison of the travel times with a travel time curve obtained from the shallow water shear velocity depth curve of Figure 16 shows excellent agreement. The results of the comparison are shown in Figure 19. On the same figure are plotted the travel times for station LRB-78–79 on the Continental Shelf off Cape Cod. These points, observed in 1948, had been previously plotted as a reversed line on a travel time graph, but no explanation for the line had been advanced. On Plate I are shown sample records illustrating occurrence of arrivals interpreted as shear waves in shallow water sediments.

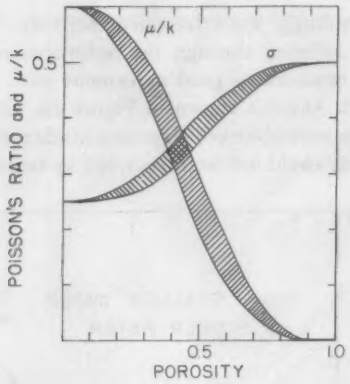

FIG. 18. Dependence of μ/k and Poisson's ratio σ upon porosity. The width represents the range of values between the choices of exponent $n=4$ and $n=5$ in Equation 12.

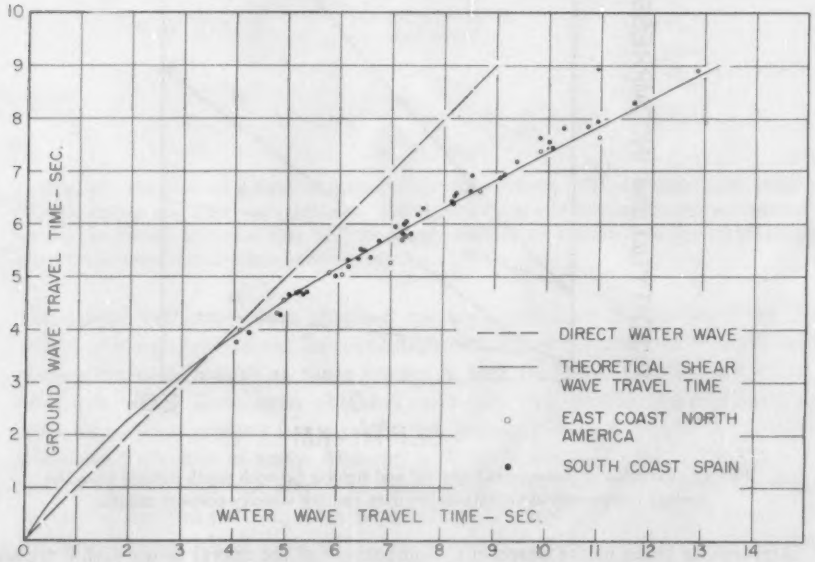
GROUND WAVE TRAVEL TIME - SEC.
WATER WAVE TRAVEL TIME - SEC.
DIRECT WATER WAVE
THEORETICAL SHEAR WAVE TRAVEL TIME
EAST COAST NORTH AMERICA
SOUTH COAST SPAIN

FIG. 19. Comparison of the theoretical travel time curve derived from calculated shear velocity in shallow water sediments with observed travel times.

In deep water sediments refracted shear waves by paths within the sediment would be unobservable with surface shots and receivers if the shear velocity-depth curve is that of Figure 16. Only by bottom recording of bottom-fired shots could such arrivals be directly observed.

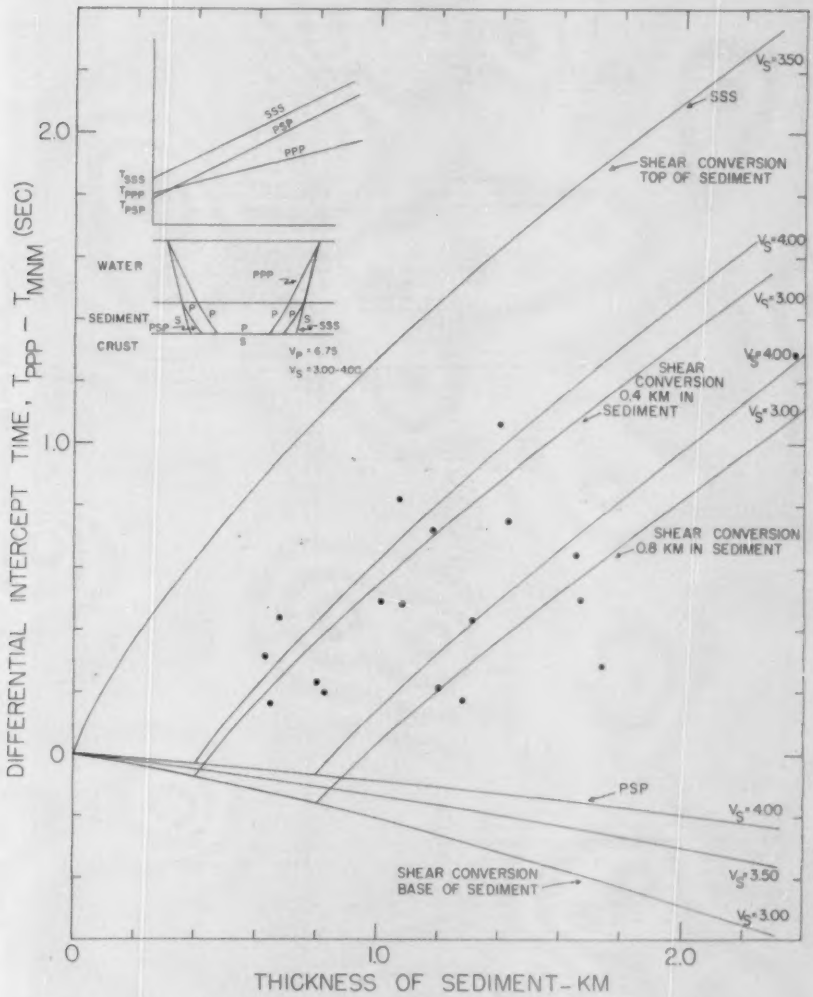

FIG. 20. Comparison of observed with calculated zero range intercept times for p and s waves refracted in the intermediate layer in deep water refraction stations. Calculated curves are shown for shear conversion at the top and bottom of the sediment and for two intermediate locations for shear conversion. T_{MNM} represents alternatively T_{SSS}, T_{PSP} or a path intermediate between the two

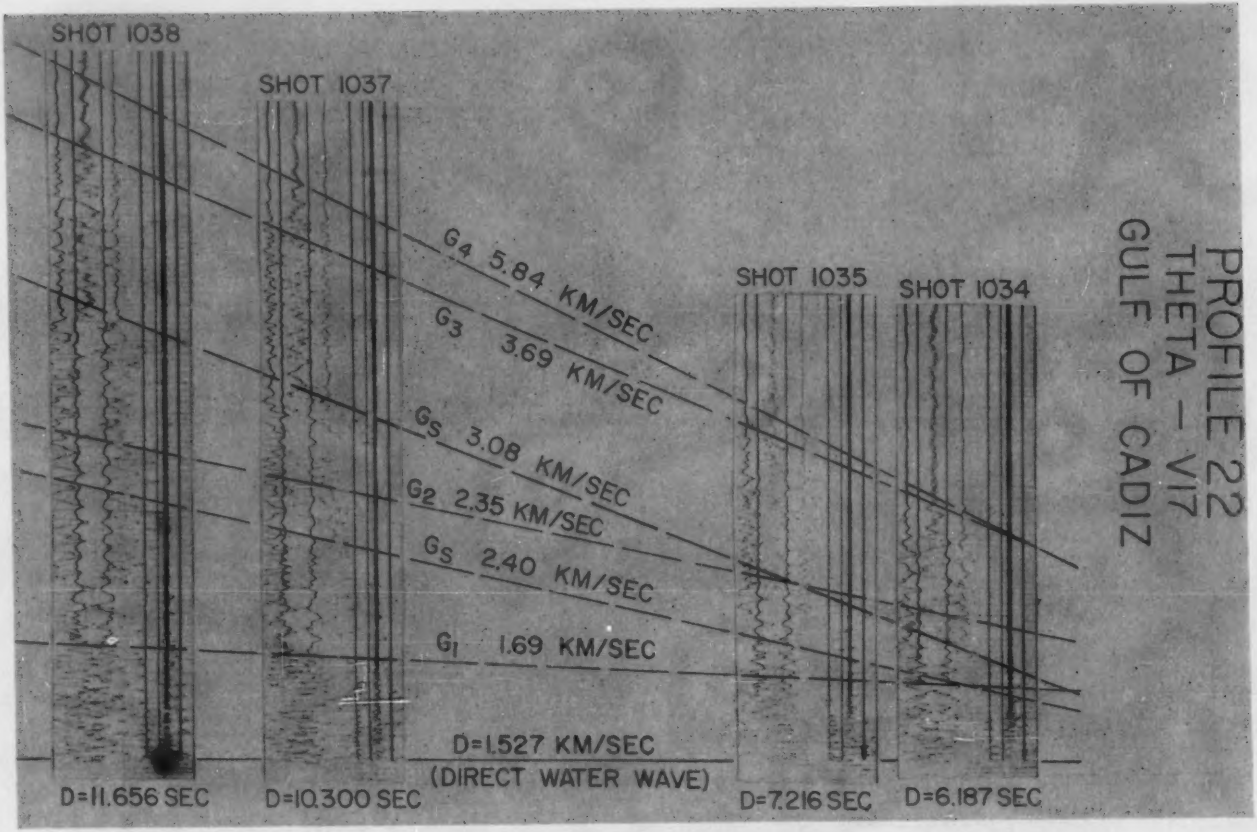

PLATE I. Sample records, Gulf of Cadiz, showing compressional and shear arrivals.

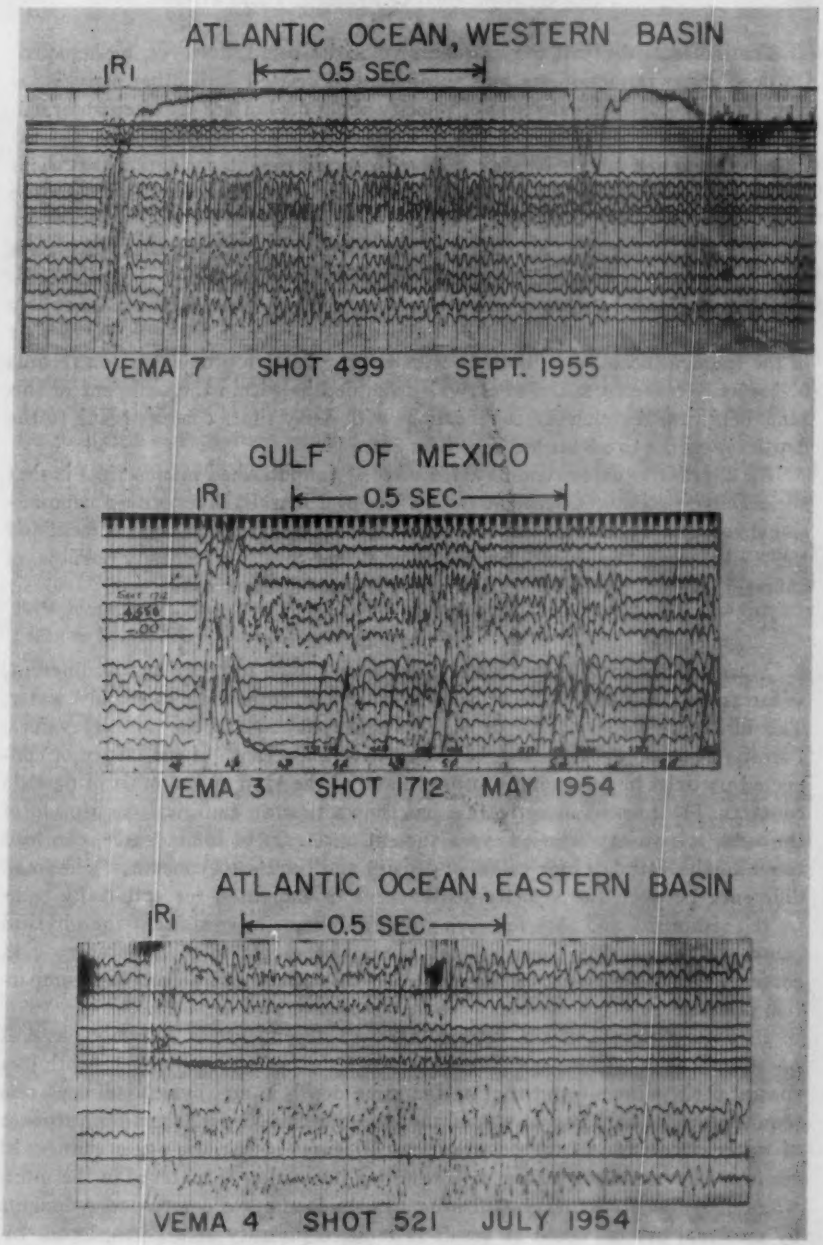

PLATE II. Vertical reflection records from the Atlantic Ocean and Gulf of Mexico. A strong reflection occurs between 0.4 and 0.5 seconds after the bottom arrival.

The indirect effects of the low shear velocities could, however, be detected. On deep water refraction stations shear lines associated with other arrivals interpreted as compressional waves of velocity about 6.4 km/sec are often observed. J. I. Ewing and G. H. Sutton of this laboratory have noticed (unpublished data) that the shear line intercepts are too large to permit the interpretation that shear conversion takes place at the refraction interface. The data would support the view that shear conversion must occur in the sedimentary column somewhere above the refracting interface. Figure 20 shows that the delay in shear arrivals is not large enough to be interpreted in terms of shear conversion at the water sediment interface. Conversion at a depth of 0.4 to 0.8 kilometers in the sedimentary column would be a possibility. If so, the result is particularly interesting in view of the frequent occurrence, both on wide-angle reflection profiles and on records of normally reflected sound of arrivals from depths within the sediment in this same depth range. Such direct reflections with delay times corresponding to the depth ranges 0.4 to 0.8 sec are shown on Plate II.

An alternative explanation by J. I. Ewing (unpublished manuscript) is that shear conversion might occur at the surface of a masked layer with a compressional velocity of about 5.5 km/sec. Such a layer, lying between the sediment and the 6.4 km/sec layer, would necessarily be rather thin. It is entirely possible, of course, that examples may be found of both kinds of shear conversion.

CONCLUSIONS

Marine sediments in deep water have been shown to be distinctly different, so far as compressional wave velocity is concerned, from those in shallow water. This difference would appear to have its principal cause in the porosity values. Porosity is certainly a measure of the relative importance of the lattice of connected particles in determining stiffness, and of the kind and number of particle contacts. The present investigation has shown that an empirical description of the velocity-porosity relation, even though uncertain to some degree, can lead to reasonable estimates for values of density and the elastic constants. The small difference between the velocity-depth curve of Laughton for artificially compacted sediments and that for deep water sediments suggests that the physical causes for the velocity-porosity relation may be sought in the laboratory with confidence that the result will be applicable also to naturally occurring compaction processes.

The exact nature of the velocity-porosity dependence is a purely physical question. The considerable difference between the porosity at a given depth in a coastal shelf sediment and that at the same depth in an abyssal sediment also requires explanation. It is suggested that the difference depends upon the absence of water circulation in the deep water sediments. In shallow water changes of sea level, circulation of water, with resulting deposition of material in the interstices of sediments or recrystallization, and unloading of compacted sediments by erosional process could all result in reduced porosity at a given depth. In-

vestigation of specific areas by the present technique will help to settle this question.

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GEOPHYSICS, VOL. XXII, NO. 3 (JULY, 1957), PP. 553–564, 3 FIGS.

POLARITY COINCIDENCE SCHEME FOR REVEALING SIGNAL COHERENCE*

BEN S. MELTON† AND PHILIP R. KARR‡

ABSTRACT

A simple statistical procedure, based on multiple coincidence of field polarities as indicated by several receptors, offers a criterion of the existence of a signal below the general noise level. As an example, with six receptors in a field where there is a sine wave signal ten decibels below the noise level, there will be twice the number of coincidences that would be obtained for the noise alone. A scheme is shown to illustrate how an electrical system can perform the analysis and present the results continuously.

INTRODUCTION

The present paper attacks the following aspect of the general problem of detecting signal in the presence of noise. Suppose there are available several channels, each containing statistically equivalent noise and essentially the same coherent signal content, but perhaps with various time shifts among the several channels. Such an arrangement might, for example, be obtained by placing a number of receptors in a field (e.g. electromagnetic) containing both coherent (signal) content and noise. The time shifts of the signal in the various channels will be related to the geometric pattern of the coherent part of the field.

It has occurred to us to test for the presence of signals in the following way. At first, suppose for simplicity that the signal is the same in each channel; then the instantaneous amplitudes in the several channels will tend to be the same, when the signals exist, this tendency being counteracted to some extent by the presence of noise. Further, even if the agreement in amplitudes is considerably disrupted by the noise, there may still be a strong tendency for the polarities to agree. What the present scheme does is to obtain a measure of this tendency toward polarity agreement. Thus we do not actually make a detailed study of the amplitudes in the various channels, but restrict ourselves to comparing the instantaneous signs in the various channels. A surprisingly small amount of information is lost by retaining only the signs, as analysis shows. The signs in the various channels are compared at regular intervals and the number of instances in which all signs are in agreement is recorded. If, over a given period, the number of coincidences is high compared to the number expected with only noise in the channels, this is taken as evidence of the existence of signal. If there is a progressive phase shift between the signals in the various channels (corresponding to

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signals from the same source but shifted in time relative to the various channels), then the number of coincidences will be decreased. This situation may be taken care of by incorporating appropriate time delays in the several channels ahead of our sign coincidence testing device. What is envisaged in practice is to test for coincidence with several sets of time delays. The presence of signal should then show up in a large number of coincidences for one particular set of time delays.

The proposal here presented is the result of persistently asking the question—"How can we obtain a useful answer which is related to the mutual correlation of three or more signals?" It can be shown, for instance, that arbitrary multiplication of signal ordinates may not be used as a basis for multiple correlation, so that this means of making use of signal amplitudes presents difficulties. Our scheme, on the other hand, within certain restrictions, does use a form of multiple correlation. The relationship of the present proposal for recognizing correlation to other and more basic measures of correlation will be seen in a separate paper (Melton and Bailey, 1957).

PROPOSED SYSTEM

Figure 1 illustrates a system for accomplishing the examination just described. An advancing coherent signal wave front is shown at the left of the figure, the rows of plus and minus signs indicating that the field is of some alternating nature, not necessarily sinusoidal. The group of receptors for the

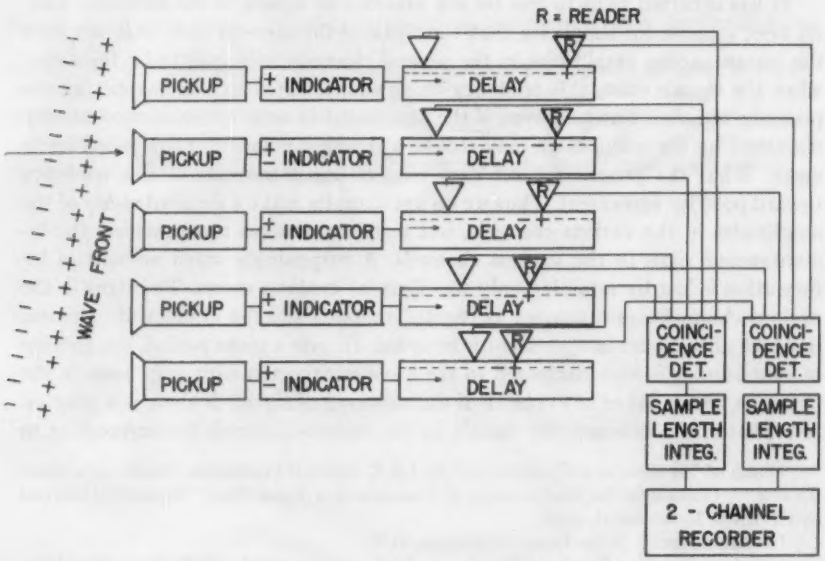

FIG. 1. Multi-correlator with five inputs, showing outputs for two sets of delays.

signal is followed by polarity indicators, and these in turn are followed by delay lines, which in this arrangement need carry only the signal polarities as binary decisions. Appropriately disposed readout devices, shown by the triangles, serve to pick off the delayed signals, which then pass on to a coincidence detector, an integrator and the recorder, in turn. The coincidence detector will deliver a pulse each time a coincidence of signs occurs, the integrator will sum these pulses over any predetermined interval or sample length, and the reconstituted information will appear as an amplitude in a recorder channel. Thus the final record will be a time summation of signal polarity coincidence, the amplitude being a statistical measure of the signal coherence.

In Figure 1, two recording channels are indicated. However, it is obvious that only those readout devices which are properly located along the delay lines will deliver coincident signs for any given direction of wave propagation, so that it is necessary to provide as many recording channels as there are separate examinations of wave front direction, if simultaneous processing is desired. It is possible that under some practical conditions it will be more convenient to interchange the processing order of the delay line and the polarity indicator devices. If this is done, the delay line must carry signal amplitudes, but system flexibility may be enhanced.

The basis for the present scheme, as outlined in the introduction, is that if over a certain interval of time, a number of coincidences of sign is found in the n channels, deviating greatly from the number expected with pure noise, one may infer that there is considerable likelihood of presence of coherent signals in the channels during the interval considered. The probability of obtaining a given number k_N of coincidences in m samplings, with pure noise, is easily calculated.[1] This probability rapidly becomes very small as k_N departs greatly from $\bar{k}_N$, the expected value of k_N. The probability of obtaining exactly k_N coincidences is

$$\binom{m}{k_N} p^{k_N} q^{m-k_N} \tag{1}$$

where

$$\binom{m}{k_N} = \frac{m!}{k_N!(m - k_N)!}$$

$$q = 1 - p$$

and p is the probability of obtaining a coincidence in one trial. If the number of channels is n,

$$p = 2(\tfrac{1}{2})^n. \tag{2}$$

[1] Throughout the present preliminary report we ignore the fact that in general the noise amplitude at one particular sampling instant is somewhat correlated with the noise amplitudes at previous and following sampling instants; i.e., that these amplitudes are not really independent.

The probability of obtaining at least k_N coincidences in m trials is

$$\sum_{j=k_N}^{j=m} \binom{m}{j} p^j q^{m-j}. \tag{3}$$

As an example, consider the result of sampling the coincidences of sign 48 times in 4 channels. The expected number of coincidences on the basis of noise is $48 \times \frac{1}{8} = 6$. Of course, other numbers near 6 have nearly as great probabilities of occurrence. Table 1 shows some cases of interest computed by means of the above formulae. The argument of Table 1 is k_N, the number of coincidences, or "hits." As indicated by the column headings, the table gives the probabilities that the given integral values of k_N will result from 48 tries, and also the probabilities that the number of coincidences will be equal to or greater than k_N. Table 1 illustrates how rapidly the chance of obtaining, with noise only, a number of coincidences k_N greater than $\bar{k}_N$ decreases as k_N becomes substantially greater than $\bar{k}_N$. Thus, if the number of coincidences found is considerably greater than $\bar{k}_N$, we have evidence of the existence of coherent signal.

TABLE 1

PROBABILITIES OF k_N VALUES; 48 SAMPLINGS; NOISE ALONE PRESENT

k_N	Probability of Obtaining *Exactly* k_N		Probability of Obtaining *at Least* k_N	
	4 Channels	6 Channels	4 Channels	6 Channels
0	.0016	.22	1.000	1.00
1	.011	.34*	.998	.78
2	.038	.26	.987	.44
3	.083	.13	.95	.19
4	.133	.046	.87	.063
5	.168	.013	.73	.017
6	.172*	.0030	.57	.0037
7	.147	.00058	.39	.00069
8	.108	.000096	.24	.00011
9	.068	.000014	.14	.000015
12	.0083	.000000019	.013	
16	.00011		.00014	
20	.00000035		.0000004	

* Peak probabilities.

CONSIDERATIONS OF "SIGNAL-TO-NOISE RATIO"

To obtain a rough idea of how effective this scheme may be in detecting the presence of coherent signal in noise, we may calculate the number of coincidences expected with a signal of given form and amplitude. Suppose we have at a given moment in one of the channels a definite signal amplitude A_1 superimposed upon a random instantaneous noise amplitude N_1. The noise is assumed to have a Gaussian amplitude distribution with a mean value of zero and a variance N_{rms}^2. The probability density of the noise amplitude N is

$$\frac{1}{\sqrt{2\pi}N_{\text{rms}}}\exp\left[-\frac{N^2}{2N_{\text{rms}}^2}\right]. \tag{5}$$

The probability P_1 that the amplitude A_1+N_1 is positive is the probability that N_1 has a magnitude between $-A_1$ and ∞, or

$$P_1 = \frac{1}{\sqrt{2\pi}N_{\text{rms}}}\int_{-A_1}^{\infty}\exp\left[-\frac{N^2}{2N_{\text{rms}}^2}\right]dN$$

$$= \frac{1}{\sqrt{\pi}}\int_{-A_1/\sqrt{2}N_{\text{rms}}}^{\infty} e^{-x^2}dx. \tag{6}$$

In terms of the standard "error integral" $\Phi(x)$, defined as

$$\Phi(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt,$$

(Jahnke and Emde, 1945, p. 23), we have

$$P_1 = \frac{1}{2}\left[\Phi(\infty) + \Phi\left(\frac{A_1}{\sqrt{2}N_{\text{rms}}}\right)\right]$$

$$= \frac{1}{2} + \frac{1}{2}\Phi\left(\frac{A_1}{\sqrt{2}N_{\text{rms}}}\right) \tag{7}$$

The probability that A_1-N_1 is negative is

$$1 - P_1 = \frac{1}{2} - \frac{1}{2}\Phi\left(\frac{A_1}{\sqrt{2}N_{\text{rms}}}\right).$$

Now if we have several channels, our experimental set-up may be such that in general there will be at any given moment a different value of the signal in each of the channels. In many possible cases there would be a progressive phase shift or time delay from channel to channel. To keep the analysis simple we shall consider the case in which the signal is the same in all channels, although any other case could be worked out. Where there are progressive phase shifts, the effect of equal signals could be obtained by incorporating an appropriate delay from channel to channel in our sign-coincidence testing device.

If we have n channels, each having at time $t=0$ the same instantaneous signal amplitude A_1 superimposed upon a random noise amplitude, the noise being statistically the same in all channels, the chance that in each of the n channels the resultant instantaneous amplitude is positive is P_1^n, and the corresponding chance for negative amplitudes is $(1-P_1)^n$. The chance that the sign of the amplitude is the same in all n channels at time $t=0$ is

$$p\left(n, \frac{A_1}{N_{\text{rms}}}\right) = P_1^n + (1 - P_1)^n. \tag{8}$$

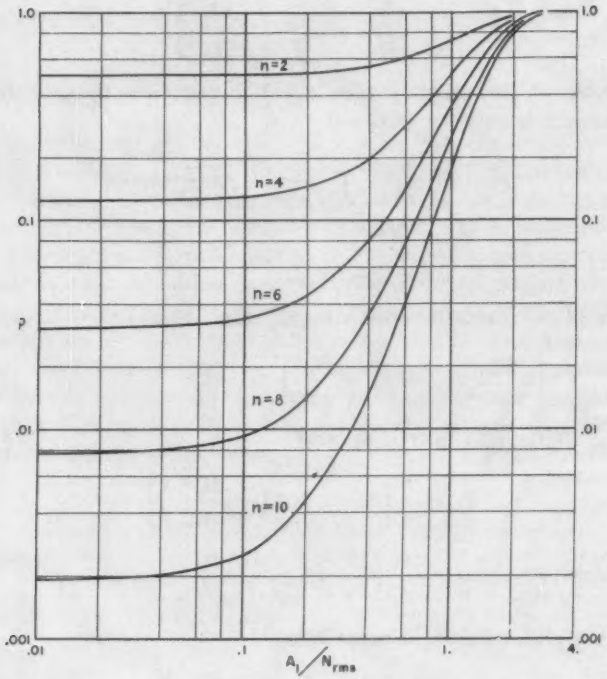

FIG. 2. Plot of $p(N, A_1/N_{rms})$ versus A_1/N_{rms} for several values of n.

Figure 2 is a plot of $p(n, A_1/N_{rms})$ for a range of A_1/N_{rms} and for several values of n.

Now suppose at some later moment $t=\Delta t$ we again sample the signals in the n channels. If the signal amplitude is A_2 then we get by equations (7) and (8) a new value of p appropriate to this new signal value A_2. After m such samplings, at times 0, Δt, $2\Delta t$, etc., the expected number of coincidences $\bar{k}_{N+S}$ is

$$\bar{k}_{N+S} = \sum_{j=1}^{j=m} p\left(n, \frac{A_j}{N_{rms}}\right). \tag{9}$$

The expected value of the fraction of m times that sign coincidence is found is

$$\bar{a} = \frac{\bar{k}_{N+S}}{m} = \frac{1}{m} \sum_{j=1}^{j=m} p\left(n, \frac{A_j}{N_{rms}}\right). \tag{10}$$

For continuous sampling we may write for the expected value $\bar{a}'$ of the fraction of time that a coincidence of sign exists

$$\bar{a}' = \frac{\int_0^T p\left(n, \frac{A(t)}{N_{\text{rms}}}\right) dt}{T} \tag{11}$$

where $A(t)$ is the signal amplitude as a function of t, and T is the total time over which the sampling is taken. It is seen that $\bar{a}$ is an approximation for $\bar{a}'$ and $\bar{k}_{N+S}\Delta t$ is an approximation for the numerator of equation (11).

In the case of pure noise in all channels, we see from equation (3) that the expected number of coincidences is

$$\bar{k}_N = m2^{1-n}$$

also

$$\bar{a} = \bar{a}' = 2^{1-n}. \tag{12}$$

Using the basic curves of Figure 2, we can calculate the coincidence probabilities for any form of signal. The procedure is to determine the instantaneous signal amplitudes at a number of points over a finite interval of time, and, entering the proper curve, read off and sum the coincidence probabilities. If we do this for a sine wave, we can obtain results for several cases of interest.

As an example, using the above analysis, consider the case of a sine wave signal whose peak amplitude $A_{\text{peak}} = \sqrt{2}N_{\text{rms}}$. In this case the average signal power equals the average noise power. Let us assume that $n = 6$ and that we sample 16 times per cycle. We find, using Figure 2 to obtain the p's, that

$$\bar{k}_{N+S} = 5.36 \text{ per cycle}$$
$$\bar{k}_N = 0.5 \text{ per cycle}$$

so that

$$\frac{\bar{k}_{N+S}}{\bar{k}_N} = 10.8.$$

We may consider then that in a sense this device considerably increases the signal-to-noise ratio. Starting with signal power equal to noise power, we have obtained an "output" (expected number of coincidences) 10 times greater in the presence of the signal than in its absence. Even in the case where the signal power is 10 decibels below the noise, the use of six receptors will deliver twice the number of coincidences expected for the noise alone.

Table 2 presents cases for signal power equal to noise power, signal 6 decibels below noise, and signal 10 decibels below noise. In this table the first column lists n, the number of detectors. The second column gives $\bar{k}_N$ the expected number of coincidences or "hits," on the basis of noise alone, with 16 samplings. The third column gives $\bar{k}_{N+S}$ the expected number of hits with noise and sinusoidal signal present, per cycle of the signal, on the basis of 16 equally spaced samplings per

TABLE 2

MOST PROBABLE NUMBER OF "HITS" PER CYCLE AND HITS RATIO, FOR 16 SAMPLINGS PER CYCLE

No. of Channels, n	k_N	Case for Signal = Noise		Case for Signal 6 db Below Noise		Case for Signal 10 db Below Noise	
		$\bar{k}_{N+S}$	$\bar{k}_{N+S}/\bar{k}_N$	$\bar{k}_{N+S}$	$\bar{k}_{N+S}/\bar{k}_N$	$\bar{k}_{N+S}$	$\bar{k}_{N+S}/\bar{k}_N$
2	8.	11.4	1.4	9.2	1.1	8.5	1.1
4	2.	7.5	3.7	3.8	1.9	2.7	1.4
6	.5	5.4	11.	1.8	3.5	1.0	2.0
8	.125	4.0	32.	.90	7.2	.39	3.1
10	.031	3.2	104.	.48	15.	.15	4.7

cycle; the noise power level is assumed to equal signal power level. In column four, the ratio $\bar{k}_{N+S}/\bar{k}_N$, the "hits" ratio, is given. Columns five to eight give $\bar{k}_{N+S}$ and the hits ratio for those cases in which the noise power level is 6 decibels and 10 decibels below the signal level.

Table 2 reveals some limitations. As the number of channels is increased, although the hits ratio increases we may find, when the duration of sampling is limited, that there are too few hits to work with. Of course, matters may be improved by taking the sampling points closer together if this is feasible from the instrumentation point of view. A complication may set in when the sampling moments are too close together, along the lines mentioned in footnote 1; the interpretation of results becomes somewhat more involved because of the correlation of noise amplitudes with preceding and following amplitudes.

It should be noted that with a given signal, with identical signals and statistically equivalent noise in all channels, the expected value $\bar{k}_{N+S}$ decreases with increasing n, but the "hits ratio" $\bar{k}_{N+S}/\bar{k}_N$ increases. To show this it is merely necessary to show that

$$\frac{P^n + (1-P)^n}{2(\frac{1}{2})^n} \geqq \frac{P^{n-1} + (1-P)^{n-1}}{2(\frac{1}{2})^{n-1}} \tag{13}$$

where $P < 1$. The statement (13) is true if

$$2P^n + 2(1-P)^n \geqq P^{n-1} + (1-P)^{n-1}$$

or if

$$P^{n-1}(2P-1) - (1-P)^{n-1}(2P-1) \geqq 0$$

or

$$(P^{n-1} - Q^{n-1})(P-Q) \geqq 0$$

where

$$P + Q = 1.$$

But the last statement is true; the equality sign holding only for $P=Q=\frac{1}{2}$. Therefore (13) is true so that $\bar{k}_{N+S}/\bar{k}_N$ increases with increasing n, in agreement with "intuition." In a general way we can say that a desirable value of n is one large enough to give a high value of $\bar{k}_{N+S}/\bar{k}_N$, but small enough to give a sufficiently great $\bar{k}_{N+S}$.

If desired, one may study in more detail the distribution of the number of coincidences. Abbreviating the notation used in equation (8), let p_i be the probability of a coincidence at the ith sampling (when $A=A_i$); let $q_i=1-p_i$. Then the probability of obtaining exactly k_{N+S} coincidences is the sum of those terms in the product

$$\prod_{i=1}^{m} (p_i + q_i)$$

which contain as factors exactly k_{N+S} p's. In this way one may obtain the frequency distribution of the number of coincidences with any set of p's. We may also obtain with little trouble the first three moments of the distribution. These are

$$\bar{k}_{N+S} = \sum_{i=1}^{m} p_i$$

$$\sigma^2 = \overline{(k_{N+S} - \bar{k}_{N+S})^2} = \sum_{i=1}^{m} p_i q_i$$

$$\overline{(k_{N+S} - \bar{k}_{N+S})^3} = \sum_{i=1}^{m} p_i q_i (q_i - p_i)$$

Although the frequency distribution is not normal, the relative values of σ and $\bar{k}_{N+S}$ serve to indicate roughly the degree of spread of the distribution. As a matter of fact, in many cases the distribution will be close to normal.

The frequency distribution of k_{N+S} has been worked out for a number of cases, some of which are shown in Figure 3, along with the frequency distribution of k_N which appeared in Table 1. The curves have been drawn for 48 trials. They show the distributions for noise only, signal and noise r.m.s. values equal, and signal 6 decibels below noise. Figure 3 gives the results for four and six receptors. The fact that the curves are not sharply peaked and that they tend to cross one another nearer their peak values as the signal level is decreased, points up the desirability of obtaining a sufficiently large sample. A larger sample has the effect of sharpening up the curves, thus tending to make easier the reaching of a decision concerning the presence of signal.

It may be noted that if definite assumptions as to *a priori* probabilities of the presence of signal can be made, then we can invoke the aid of Bayes' theorem and

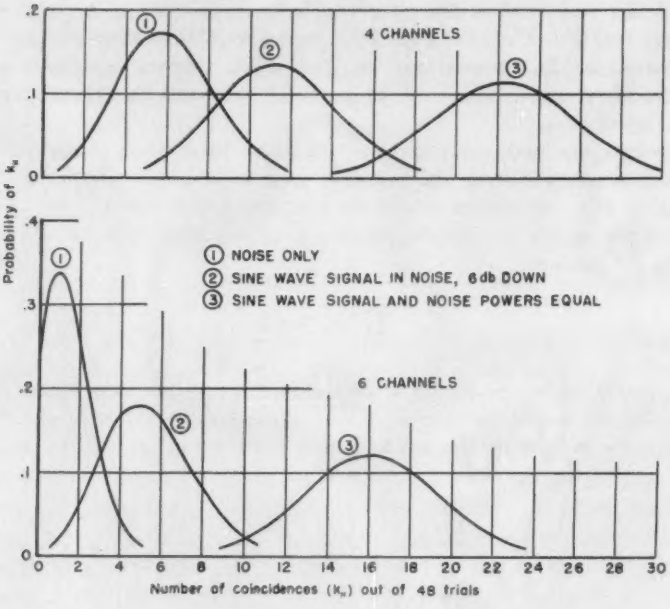
4 CHANNELS
6 CHANNELS
① NOISE ONLY
② SINE WAVE SIGNAL IN NOISE, 6db DOWN
③ SINE WAVE SIGNAL AND NOISE POWERS EQUAL
Probability of k_n
Number of coincidences (k_n) out of 48 trials

FIG. 3. Probability curves for coincidences in 48 trials.

related concepts to help us reach a decision as to the likelihood of presence of signal for a particular set of observations.

THE "QUORUM NUMBER" CONCEPT

So far, for the sake of simplicity, the discussion has covered only the proposition that complete agreement of signs at a given instant would be considered to constitute a "coincidence" for the statistical procedure. This is the simplest process and the easiest to instrument, but not the only possible procedure. In particular, any majority agreement among signs could be used. To examine this idea conveniently, we may invent a device called a "quorum number," defining this quantity as the number of sign agreements required out of the total number of channels compared. The acceptance of, say, eight out of ten sign agreements as a "coincidence" can then be expressed by the definition

$$\text{Q.N.} = 8(10).$$

We cannot completely settle here the question of the relative merits of "quorum number" versus "no quorum number." However, it is easy to show that if one calls sign agreement of at least $n-1$ out of n channels a "coincidence," then the ratio $\bar{k}_{N+S}/\bar{k}_N$ obtained in this way is less than the value of $\bar{k}_{N+S}/\bar{k}_N$ obtained with

the original definition of a "coincidence," when the number of channels is n in both cases. In fact we shall prove a stronger statement; namely, that the value $\bar{k}_{N+S}/\bar{k}_N$ obtained with the quorum number of $n-1$ out of n, is less than the $\bar{k}_{N+S}/\bar{k}_N$ obtained with only $n-1$ channels when we define sign agreement in all $n-1$ channels as constituting a coincidence. To prove this we consider the values of $\bar{k}_{N+S}/\bar{k}_N$ in the two cases, with *one* sign sampling, where the chance of a positive sign in one channel is p, and $p+q=1$.

Define

$(\bar{k}_{N+S}/\bar{k}_N)_{n,q} = (\bar{k}_{N+S}/\bar{k}_N)$ with n channels and a Quorum Number of $n-1$ out of n,

and

$(\bar{k}_{N+S}/\bar{k}_N)_{n-1,0} = (\bar{k}_{N+S}/\bar{k}_N)$ with $n-1$ channels, with no "Quorum" arrangement.

Then

$$(\bar{k}_{N+S}/\bar{k}_N)_{n,q} = \frac{p^n + q^n + n(p^{n-1}q + pq^{n-1})}{(2+2n)(\frac{1}{2})^n} \tag{14}$$

and

$$(\bar{k}_{N+S}/\bar{k}_N)_{n-1,0} = \frac{p^{n-1} + q^{n-1}}{(\frac{1}{2})^{n-2}}. \tag{15}$$

We find, after some manipulation

$$(\bar{k}_{N+S}/\bar{k}_N)_{n,q} - (\bar{k}_{N+S}/\bar{k}_N)_{n-1,0} = \frac{2^{n-2}(1-n)}{1+n}(p^{n-1} - q^{n-1})(p-q)$$
$$\leqq 0 \text{ if } n > 1, \tag{16}$$

since $p^{n-1}-q^{n-1}$ and $(p-q)$ have the same sign. This proves the statement above.

However, it does not follow that the quorum number is of no use. If we are severely restricted on sample length, we may find that while the hits ratio can be made large by increasing n, it is of little value because of the small number of hits involved. It is of little value to make the expected coincidences with noise alone much less than, say, one out of 48 tries, if the number of coincidences expected when signal is present is only two or three. Here our statistics are too "lean." In such a case, it turns out that when we have upwards of eight or ten receptors we can improve matters quite markedly by using quorum numbers of 7(8), 8(10) or 9(10), instead of insisting on total agreement.

CONCLUSIONS

It seems to us that the usefulness of the proposal is best outlined by listing its major characteristics, as follows:

1. It appears to be most useful where the number of receptors may be greater than two but is limited to a small number. While the use of a large number of channels is possible through the Quorum Number modification, the complexity of the system may offset the advantages.
2. It does not require previous knowledge of the signal frequency except quite generally. Some knowledge of signal frequency and duration is of course implied in system design and in choice of the frequency of sampling and period of integration.
3. The form of final presentation permits continuous processing, the result being available after the lapse of one sampling period.
4. Its ultimate ability to recognize signal in noise is limited by the duration of the signal.
5. It does not deliver a signal of the form of the original, but a number or amplitude which is a criterion of signal existence.

ACKNOWLEDGMENTS

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MULTIPLE SIGNAL CORRELATORS*

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ABSTRACT

Methods of correlation of any number of input functions or signals to be compared are discussed. It is shown that correlation values can be obtained from any one of several arithmetic processes which measure the degree of similarity of the inputs, and that these processes can be mechanized. Included are a simple addition, a sign-coincidence scheme, and two processes based on analysis of variance. The discussion of analysis of variance procedures as applied to signals shows that the answers can be interpreted in terms of statistical significance, that measurements of coherent signal power can be made, and that the accuracy of such measurements is greatly improved as the number of input signals is increased. Signal-to-noise ratio is shown to be uniquely related to statistical significance, and signal detectability is plotted as a function of number of inputs and signal duration. Several means of presentation of data are suggested and illustrated.

INTRODUCTION

The detection of signals which arrive by more than one parallel channel, or which travel in some continuum and are distorted by noise in the signal band is important in many physical problems. Necessary to an adequate treatment of the problem are a number of statistical concepts, which, in the past, have frequently been overlooked. One possible reason for this is that most of the statistical methods needed have been developed specifically for the field of biometrics. In attempting to bridge the gap between biometrics and other physical sciences, one faces the problem of definitions and terminology. Since the present paper is chiefly a discussion of devices which treat incoming energy by converting it to electrical signals, we have chosen to employ engineering terminology where possible, defining the statistical terms only when necessary. A rigorous proof of the statistical theory is not included because it is well covered in the literature (Fisher, 1948; Hoel, 1954; McNemar, 1955).

The discussion which follows will define means for the comparison of several similar functions or time series, will analyze the processes required of devices which perform such comparisons, generally called correlators, and will show in particular how the statistical treatments devised by R. A. Fisher (1948) may be effectively used for this purpose. It is intended that the paper shall provide realistic guidance to the practical advantages and limitations of automatic correlators.

BASIC CONCEPTS

Whether or not we use the term "signal" in the restricted engineering sense, we can say that the correlation of a multiplicity of signals is the process of evalu-

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ating the information common to all of them. It can be thought of as an over-all process which strives to answer one or both of two questions. One question is, "What is the information common to most or all of the signals examined?" The other question is, "What is the degree of commonness between all signals examined?" The simplest procedure followed to answer the first question may be to form an arithmetical average of corresponding ordinates. This implies several assumptions, including the assumption that all of the signals have equal weight. Answers to the second question can be obtained in different forms, but, in general, these forms do not resemble the form of the answers to the first question.

The following discussion will deal almost entirely with the second question, the degree of commoness between signals. This is often thought of as the "coherence," because signals picked up from a uniform or "coherent" signal field will show a common pattern, and the fact that this pattern exists in common is often used as evidence that a coherent field exists. Therefore, a good test for a common pattern in a group of signals is, by inference, a good test for the existence of a coherent field from which they were derived. However, this test for a common pattern need not reveal the form of the pattern.

A study of the problem shows that many tests can be devised to reveal the existence of a common pattern, and that the disclosure of its exact form may have little or no bearing on the usefulness of the test. It is perhaps easiest to illustrate the usefulness of a variety of tests by citing some examples, as follows:

1. *Binaural location of a sound.* Even though the sound is unrecognizable, or transmits no particular meaning to our brain, its existence and direction are recognized.
2. *Subsurface geologic structure by electrical well-logging.* The electrical logs are graphical plots of electrical resistivity measurements. Even though there is no unique relationship between any single geologic bed and its electrical resistance, the graphic plot can be matched with others from nearby wells to show, on a probability basis, the shape of the geological structure.
3. *Exploration seismograph techniques.* Commercial reflection and refraction seismographs record the output from many pick-ups on adjacent signal traces. Reflections and refractions are identified by the fact that the traces show an alignment of similar wave forms across the record. In this instance, as with the electrical well logs, the correlation is performed within the brain of the person viewing the records. It is difficult to say precisely what reasoning leads to the conclusion that the wave forms are similar, since they are so recognized even in cases where they have greatly different amplitudes and are distorted by unexplained "noise."

One very important point may be developed from the above and other examples. All examinations of pattern to determine common content imply a trial of the patterns in several combinations with a view toward finding the best matching combination. This may be done by the brain so quickly that it is not recognized as a conscious act; nevertheless, it is a vital part of the process, and any

machine devised for the same purpose must include this action. The case where the trial for pattern match is made for only one combination may be useful under certain restricted conditions; but it does not constitute a full processing, and will not use to full advantage the power of the correlation process.

The act of trying various fits of the several patterns may be thought of as "scanning" the data; a number of "scans" can be performed either simultaneously or sequentially, depending upon machine design. However, each scan must include a sufficient length of pattern or a sufficient time sample so that the statistical result has appreciable significance; a scan across single values of the several signals has little usefulness in any correlation procedure. Thus a memory of some nature is implied, and a decision on the matching of signal patterns cannot be reached prior to the examination of a time sample of the signals.

Upon completion of the scanning process, the information available may result in the following:

1. A decision as to which combination or combinations of signal patterns showed the best match.
2. Magnitudes showing the perfection of match at the best matching position, or at all relative positions scanned. These magnitudes may be called correlation coefficients or correlation ratios.
3. An estimate to indicate the significance of the quantity used as a measure of the perfection of matching. To test the significance of a correlation magnitude, we calculate the probability that it might be derived, by random sampling, from uncorrelated data. If the probability is low, the correlation is regarded as significant.

Generally speaking, the practical purpose of any mechanical or human correlator, as applied to electrical or other signals, is to detect, and perhaps measure, desired components among undesired ones. This is possible only under the condition that the statistical distribution of the desired components is different from that of the undesired components. There are restrictions on both distributions. It often happens that the desired components are those of a single signal field, of planar or nearly planar wave front, whether or not the direction is specified; and that the "noise" comes from so many directions that it can be considered as being statistically random in the region of observation. Under at least these restrictions, a mechanical correlator can perform a useful function.

In the author's experience, the most elusive concept concerned with the correlation of several signals is the multi-dimensional nature of the statistical processing. For the case of only two signals, the correlogram can be presented as another function resembling a signal, this function being plotted as amplitude versus relative time or some equally simple parameter. However, the introduction of a third original signal implies comparison for the possible combinations of three signals, so that any graphical representation must partake of the nature of a curved surface. This is the way one may represent the melting point of a three-element alloy as a function of its composition. This line of reasoning points up

the difficulty of representing correlograms for more than three signals in a space of only three dimensions, but the limitation is only one of our limited imagination and the usual forms of data presentation. It does not preclude expression of the correlation function in some properly conceived form. However, to be useful in a practical sense, the correlation function needs to be in a form which allows an observer or another machine to make decisions easily, and this imposes severe restrictions. The only practical solution which appeals to the author is to have the correlation machine deliver a number or a measurable magnitude which appears as a function of the various trial matchings of the incoming signals. If the delivered number or magnitude is to indicate a good match, the machine must at least approach the position of good matching in its trials.

A complete correlation function can only be represented in terms of all possible combinations. However, the physical conditions are often such that many of the statistically possible combinations will not result in high correlation numbers for the signals of interest. For example, a linear array of pick-ups in the field of a signal from any one direction can only respond in succession to a signal from that direction. If only such signals are of interest it may seem somewhat pointless to examine pick-up outputs in some other order. However, even though the scan position for best possible signal match may be known from the physical conditions, there is generally an advantage in making a number of trial scans for positions expected to yield correlation quantities of the same level as would be obtained from completely random signals. Otherwise, evaluation of the correlation magnitude delivered by the machine depends upon comparison of this magnitude with the magnitude yielded at some previous time when the signal of interest was known to be absent. In fact, this may be considered as a point of difference between most ordinary detection processes and the multiple correlation process as defined here. The usual detection scheme sets up a signal examination procedure based upon a presumed best type of examination; the correlation process here defined compares the results of several examinations to find the combination which yields the highest output. Thus the deliberate programming of inputs into a machine correlator in positions of poor match can provide a "zero" output for reference.

Basically, the order selected for the machine trials is immaterial, so long as it is known or recorded in a manner which permits interpretation. As implied above, it is not even necessary that the individual scans correspond to physically realizable signal fields. However, if there are several possible signal fields, as from several directions, it may be desirable to scan for these different directions and to use these scans as part of the statistical information.

Before discussing the machine processes in detail, we should briefly review certain ideas on signal amplitude. Almost any signal can be thought of as perturbations in a field of stress—elastic, electric, magnetic, or fluid pressure, as the case may be. Such perturbations may be represented as deviations greater or less than some mean, and this mean can be represented as a zero line, with the devia-

tions labeled positive or negative by convention. It is important to distinguish between this definition of a positive or negative signal and the definition of some statistical values which employ these same algebraic operators. In particular, the term "negative correlation" has a very restricted meaning. In the case of the correlation of only two signals, negative correlation is taken to mean the Pearson product-moment correlation coefficient which is obtained when two similar wave forms are matched with their polarities in opposition—a somewhat different concept than we shall use in this discussion.

On the other hand, a signal amplitude of any duration can be defined in terms of power, which cannot be negative. Also, as long as strain is linear with stress, flux or current linear with potential, etc., the power will be proportional to the square of the linear amplitude measure of the perturbation.

STATISTICAL PROCEDURES

The practical problem of designing a correlator will usually revolve around choice of a statistical procedure which can be instrumented for the signals at hand. Of the procedures given below as examples, the sign-coincidence method appears to be more easily adapted to high-speed processing than the other examples, while the analysis of variance yields the most complete information. The simple addition and normalizing scheme used for the first example was devised for heuristic reasons, but there appears to be no reason why it should not be adequate in some cases.

Process I

Conceptually, the simplest process is addition. Therefore, we shall outline a procedure based on addition, though we shall have to perform a division in order to obtain a normalized output. For each step we show the electronic analogue opposite the algebraic process

Algebraic Process	Electronic Analogue
Step 1.	
At each comparison scan, sum the signal amplitudes algebraically. This means to place the signals in a trial matching position and sum the corresponding ordinates. This can be written as $\sum_{c=1}^{C} x_{ct}$, the sum of X_{ct} amplitudes over C channels.	Add the signals in proper phase.

Algebraic Process	Electronic Analogue
Step 2. Sum (integrate) over the sample length the abolute values derived from Step 1. This can be written as $\sum_{t=1}^{T} \left\lvert \sum_{c=1}^{C} x_{ct} \right\rvert$ where T measures the sample length.	Pass the summed input signals through a linear fullwave rectifier, and feed the output from this rectifier to an integrator. The integrator time constant determines the sample length.
Step 3. At each comparison scan sum the absolute signal amplitudes. This means to add absolute magnitudes of the corresponding ordinates. This can be written as $\sum_{c=1}^{C} \lvert x_{ct} \rvert$.	Pass each individual input signal through a linear fullwave rectifier, and add the outputs from these rectifiers.
Step 4. Sum over the sample length the values derived from Step 3. The expression becomes $\sum_{t=1}^{T} \left(\sum_{c=1}^{C} \lvert x_{ct} \rvert \right)$.	Pass the rectified output of Step 3 to an integrator of exactly the same time constant as that of Step 2.
Step 5. Normalize by dividing the result of Step 2 by the result of Step 4. The normalized figure will lie between zero and plus one. The final expression is then $\frac{\sum_{t=1}^{T} \left\lvert \sum_{c=1}^{C} x_{ct} \right\rvert}{\sum_{t=1}^{T} \left(\sum_{c=1}^{C} \lvert x_{ct} \rvert \right)}$.	Since analogue division by electronic means is subject to many restrictions, the suggestion here is to have the integrator output from Step 4 reduce proportionally the gain of the amplifiers providing the original signals. Alternatively, the Step 4 integrator could reciprocally control the gain of an amplifier following the integrator of Step 2.

Two points may be noted about the method just described. First, it is not restricted to the case of only two input signals. Second, it does not involve multi-

plication of one signal ordinate by another. These points are important, because the problems of manipulation of algebraic signs, particularly in attempts to combine more than two signals, have led to much confusion. It is to be noted that, among other limitations, the foregoing process will deliver plus one as long as the input signals remain of the same polarity, as, for instance, where a dc bias prevents polarity reversal.

Process II

Several years ago the author proposed a "sign-coincidence" procedure for application to the general case of any number of input signals.[1] A detailed discussion of this method is published separately (Melton and Karr, 1957). The scheme hypothesized that, if there were a small amount of coherent signal in otherwise random noise, there should be a tendency toward agreement of the signal polarities, and this tendency should be revealed by counting the number of agreements in any given time. Instrumentation of this procedure circumvents the problem of carrying signal amplitudes in any of the calculation procedures. However, the procedure is somewhat different from that of Process I, in that the signals are examined for polarity at discrete, closely spaced instants of time. All data are then processed on a digital basis up to the final integration, which may give an answer in either digital or analogue form. The steps of the process are given below.

Operation on Data	Electronic Process
Step 1.	
At each sampling instant of time, examine each signal for polarity.	At each sampling instant make the signal trigger some two-state device so that it will take up one state if the signal is positive, the other state if the signal is negative.
Step 2.	
At each comparison scan, test the signals for polarity agreement throughout the sample. This means to place the signals in a trial matching position and to note the sampling instants at which polarities agree. Agreement at each instant can be taken either as complete unanimity, or by some specified majority.	For total agreement at any instant, read out the two-state devices into coincidence "and" circuits. Majority rather than total agreement at each instant will require more complex circuitry, perhaps amplitude-level gating.

[1] "A Proposal for the determination of coherence in a signal field," paper presented before the national convention of the IRE, New York, March 4, 1952.

Operation on Data	Electronic Process
Step 3.	
In the total sample, count the number of sampling instants showing polarity agreement.	Pass the outputs from the coincidence circuits through a pulse standardizing circuit (if necessary) to an integrator, whose time constant then determines the sample length.

One of the advantages of Process II is that it is adaptable to simultaneous scanning of the data in several trial positions without undue complexity of equipment. The resulting speed of processing may be particularly advantageous under some conditions. Another advantage is the elimination of the dynamic range problem, which may be very severe with some types of signals.

Process III

A much more sophisticated processing can be based on the analysis of variance as devised by Fisher (1948). We shall digress here to outline the principles involved.

"Variance" is a term used by the statistician to define an estimate produced by dividing the sum of squares of deviations of observed quantities from their arithmetic mean by the true number of independent and unrelated observations called "degrees of freedom." It corresponds somewhat to the electrical engineering term "average power," which in a linear network is some constant times an average of squared voltage or current observations taken over a reasonable time. The difference in mathematical treatment lies in the normalizing factor, which for power is the reciprocal of the total time or total number of observations; and for variance is the number of degrees of freedom. This, for a simple average, is one less than the number of observations, since the averaging process takes away one degree of freedom. The entire matter is related closely to the statistics of limited samples.

Basically, we are making use of a set of numbers or "observations" to form estimates of the characteristics of a large parent population of numbers. In engineering terms, we can say here that we examine a systematic sample to discover the amount of coherent structure. Fisher has shown that it is often useful to resolve the variance of a variable, relative to its sample mean, into separate components, each corresponding to a source of variation. Each component of variance is derived from a corresponding sum of squares; the total variance of the sample is derived from the added sums of squares of the deviations about the sample mean. Each variance is obtained by dividing the sum of squares by the appropriate number of degrees of freedom. In general, the specification of a statistic (i.e., mean, variance, r.m.s., etc.) removes one degree of freedom from the number of items in the sample.

Analysis of variance makes use of the fact that the deviations of individual

values from the means of their sub-sets are independent of the deviations of those means from the mean of the entire set of numbers. From this we can say that the variances so obtained are independent estimates of the variance of the parent population. It has been shown that the ratio of these estimating variances, called the "F ratio" (honoring Fisher) lies close to unity only when there is no systematic pattern in the sample as examined. Therefore, we can infer the presence of such a pattern when the *F* ratio departs from unity.

In practice, the analysis can be performed on any set of numbers which can be grouped into sub-sets for testing purposes. Thus it can be used for the comparison of functions of like physical variables for evidence of their inter-dependence or correlation. Specifically, it can be applied as a test for correlation between signals from several pick-ups.

Before passing to the specific procedures for treatment of signals, we shall illustrate the analysis by performing it on a set of numbers. The set will be grouped into appropriate sub-sets, and shown as rows and columns. A look along rows can then represent one "family" of data, and a look along columns another "family." In engineering parlance, one family could be time, another family some linear dimension.

The example chosen is set up in Tables I and II, and further illustrated by Figures 1(a) and 1(b). Table I is a group of random numbers (restricted to the range 0–50) arranged in rows and columns. Table II is identical, except that to each number in the second column the number 12 has been added, and from each number in the fifth column the number 12 has been subtracted. To this degree, therefore, the figures of Table II are not random. Performing an analysis of variance on Table I yields an *F* ratio of 0.654, which is non-significant. Perform-

TABLE I

Rows	Columns				
	1	2	3	4	5
A	6	23	14	27	23
B	12	37	7	38	34
C	46	19	24	4	27
D	23	32	18	47	14
E	29	25	36	43	28

TABLE II

Rows	Columns				
	1	2	4	4	5
A	6	35	14	27	11
B	12	49	7	38	22
C	46	31	24	4	15
D	23	44	18	47	2
E	29	37	36	43	16

ing the same analysis on Table II yields an F ratio of 3.386, whereas 2.87 is a significant figure at the 5 percent level.[2]

Figure 1 contains plots of ordinates representing the numbers shown in Tables I and II. These plots could represent signals to be compared, one signal for each row of numbers, with points of comparison in time being represented by successive columns of numbers. If we adopt this concept, then we can say that the over-all pattern of the signals of Figure 1(a) is essentially non-coherent because the F ratio is much less than tabulated significant values; but the over-all pattern of the signals of Figure 1(b) has coherence because the F ratio is significant.

As applied to a group of C signals, each having T sampling points, the analysis of variance procedure can be described as follows:

Algebraic Process	Electronic Analogue
Step 1.	
At each comparison scan, add the signal amplitudes to obtain the sub-sample totals. This is the same as Step 1 of Process I, or $\sum_{c=1}^{C} x_{ct}$	Add the signals, using appropriate connection polarities.
Step 2.	
Sum the totals of Step 1 over the chosen sample length to obtain the grand total, and square this grand total. This is $\left(\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}\right)^2$	Pass the summed signals through an integrating circuit whose time constant determines the chosen sample length, and pass the integrator output through a square law device.
Step 3.	
Divide the result of Step 2 by the sample length as measured in time sampling points. This result is C times a "correction factor" which will be defined later. The expression	Since this division is by a constant, no separate electronic process is required, but the output amplitude with respect to the result of Step 4 is important.

[2] Significance at the five percent level means that there is a five percent probability that this same answer might be derived, by random sampling, from uncorrelated data. The figure 2.87 is obtained from a table of F distribution (upper five percent points), which may be found in nearly all standard texts on statistics. The table is used by entering it at the proper column with the degrees of freedom for the numerator of the F ratio, and entering at the proper row with the degrees of freedom for the denominator of the F ratio.

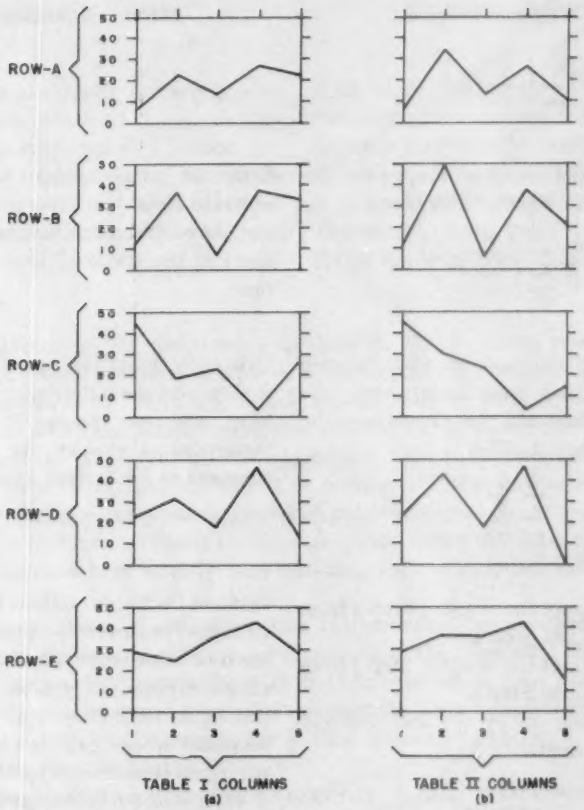

FIG. 1. Plots of ordinates represented by the numbers in Table I and II. There is common content only in (b). Analysis shows that there is less than a 5 percent probability that the correlation of (b) will be obtained from random values, while the correlation of (a) is non-significant.

Algebraic Process	Electronic Analogue
is	
$\frac{1}{T}\left(\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}\right)^2$	
Step 4.	
At each comparison scan, square each sub-sample total (Step 1) and add these totals over the sample length. This is	Pass the mixed signals from Step 1 through a square law device and then through an integrator of exactly the same time constant as for Step 2.

Algebraic Process	Electronic Analogue
$\sum_{t=1}^{T}\left(\sum_{c=1}^{C} x_{ct}\right)^2$	
Step 5. Divide the result of Step 4 by the number of signals. This is $\frac{1}{C}\sum_{t=1}^{T}\left(\sum_{c=1}^{C} x_{ct}\right)^2$	Since this division is by a constant, no separate electronic process is required, but the output amplitude here with respect to the result of Step 6 is important.
Step 6. At each comparison scan, square each signal amplitude, sum the squares and add these sums over the sample length. This is $\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}^2$	Pass each signal through a square law device, add the outputs from these devices, and pass the result through an integrator of exactly the same time constant as for Steps 2 and 4.
Step 7. (a) Subtract the result of Step 3 from the result of Step 4. (b) Subtract the result of Step 5 from the result of Step 6. (c) Divide (a) by (b) and multiply by the constant $\frac{T(C-1)}{C(T-1)}$ (Step 7(a) is C times the "between sub-sample" sums of squares. Step 7(b) is the "within sub-sample" sums of squares.) The complete expression then becomes	Perform both subtractions by opposing voltages (or currents). Since all factors are now positive, real and of restricted range, division is possible by passing the signal from Step 7(a) through an amplifier whose gain is controlled by the signal from Step 7(b), in proportion to $1/B$, where B is the signal amplitude of Step 7(b). The final constant involving C and T is an output scale factor, so the circuit may use a simple gain control which is set according to the chosen parameters.

$$\frac{T(C-1)}{C(T-1)}\,\frac{\sum_{t=1}^{T}\left(\sum_{c=1}^{C} X_{ct}\right)^2-\frac{1}{T}\left(\sum_{t=1}^{T}\sum_{c=1}^{C} X_{ct}\right)^2}{\sum_{t=1}^{T}\sum_{c=1}^{C} X_{ct}^2-\frac{1}{C}\sum_{t=1}^{T}\left(\sum_{c=1}^{C} X_{ct}\right)^2}$$

Algebraic Process	Electronic Analogue
Step 8.	
Compare the result of Step 7 with the figure obtained from an appropriate table for significance, entering the table at the column whose number equals $T-1$, and at the row whose number equals $T(C-1)$.	If an amplitude presentation is used, the magnitudes derived for given significance levels can be inscribed on the recording medium to a reasonable scale. If density presentation is used, the maximum contrast point can be set at the chosen level of significance.

Process IV

The methods so far described show how to obtain values related to the matching of several functions or signals. However, the engineer is concerned with the specific question: "With a specified amount of data, what is the signal-to-noise level at which one indication in, say, twenty, will be false?" He has in mind also the corollary question: "What changes can I make in my sampling and processing methods to improve my degree of assurance?" We shall now show that analysis of variance can yield estimates of coherent signal power and signal-to-noise ratio which are pertinent to these questions. Since the basic electronic or machine processes have already been outlined, their description will not be repeated.

As before, take as the received data the ordinates representing the signal voltages from the several pick-ups, or appearing in the associated channels. Let the datum x_{ct} represent the voltage in the cth channel at time t, and assume that this voltage is observed at equal time intervals. Then a particular set of data taken from a total of C channels, for T time instants, comprises CT numbers. This is our sample for a given "scan."

First, we should note that when we refer to a "signal" in the communications sense, even though it may include noise, we implicitly assume that we are not interested in dc components. They can be considered as bias in our data. That is, we assume that, with a total time long in comparison to any signal period of interest, a consistent dc component is due either to the nature of the channels or some chance effect of the noise. (If long-period signals are to be recognized by a slowly varying "dc" answer, then we must either take longer data samples, or compare with long-time averages of noise bias.) By this reasoning, the bias in the data is the grand average, or

$$\bar{x} = \frac{1}{CT} \sum_{t=1}^{T} \sum_{c=1}^{C} x_{ct},$$

and we are interested only in departures from this grand average as comprising our ac input. This means that we should correct our biased voltage terms by

subtraction of $\bar{x}$, or our biased "power" terms by subtraction of $\bar{x}^2$. Analogous reasoning appears in the analysis of variance, where the "correction factor" is

$$\frac{1}{CT}\left(\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}\right)^2, \quad \text{or} \quad CT\bar{x}^2,$$

since it is applied to CT squared ordinates. Thus a "correction factor" will appear in the analysis of variance procedure when it is applied to signals having a dc bias.

Now the coherence between the several channels will bring into the data a time-varying component common to all channels. Averaging the channel voltages at a given instant tends to average out independent channel noise and leave the in-phase components of any signal. We can say that successive values of this component constitute an apparent signal—"apparent" because there is no real assurance that it is not due to chance summations of noise voltages. The question then becomes, "Is this apparent signal large enough, compared to the noise background, to be significant?"

For the average channel voltage, we write

$$\bar{x}_t = \frac{1}{C}\sum_{c=1}^{C} x_{ct},$$

and remembering that there may be a dc bias, we say that our apparent signal is $\bar{x}_t - \bar{x}$.

The apparent signal power is (with a calibration factor) the mean square of the apparent signal, so the estimate of this power is

$$\frac{1}{T-1}\sum_{t=1}^{T}(\bar{x}_t - \bar{x})^2,$$

with the small sample correction of using $T-1$ rather than T in the denominator.

Now the quantity known to statisticians as "between sub-sample variance" is composed of the variance due to the deviation ascribed to the common cause and the variance due to the deviation not ascribable to the common cause. It is defined, using our notation, as

$$V_t^2 = \frac{C}{T-1}\sum_{t=1}^{T}(\bar{x}_t - \bar{x})^2$$

Thus the apparent signal power $= V_t^2/C$.

The apparent signal power has two components—the estimated signal power plus the residual noise power due to imperfect noise cancellation in the channel average. In finding the channel-average voltage, $\bar{x}_t$ the in-phase signal voltages add, and noise power adds, so the total signal voltage increases as the number of channels, C, while the "most expected" noise voltage increases as $\sqrt{C}$. Hence, dividing the total voltage by C for the channel-average gives a distributed noise voltage which varies as $1/\sqrt{C}$. This is, of course, the reason that averaging over a

large number of channels greatly reduces the noise. In our case, when we square this distributed noise voltage in the process of squaring the average "un-biased" voltage to get apparent signal power, the $1/\sqrt{C}$ coefficient of noise voltage goes to a $1/C$ coefficient of noise power. Hence:

$$\text{Apparent signal power} = (\text{estimated signal power}) + \frac{1}{C}(\text{estimated noise power}),$$

or $V_t^2 = C \cdot (\text{estimated signal power}) + (\text{estimated noise power})$.

We can estimate the noise power directly from the mean square of the deviation of the data from the apparent signal, for the entire sample, writing

$$\text{Estimated noise power} = \frac{1}{T(C-1)} \sum_{t=1}^{T} \sum_{c=1}^{C} (x_{ct} - \bar{x}_t)^2$$

and again making the small sample correction through the use of $(C-1)$ instead of C in the denominator, since the average is taken across channels.

However, the "within sub-sample variance" is defined by the statistician as that variance due to the deviation not ascribable to the common cause, and, in our notation, it would be

$$V_e^2 = \frac{1}{T(C-1)} \sum_{t=1}^{T} \sum_{c=1}^{C} (x_{ct} - \bar{x}_t)^2$$

which is identical with the expression for noise power.

Since apparent signal power $= V_t^2/C$ we have, therefore:

$$\begin{pmatrix} \text{Estimated} \\ \text{signal} \\ \text{power} \end{pmatrix} = \begin{pmatrix} \text{apparent} \\ \text{signal} \\ \text{power} \end{pmatrix} - \frac{1}{C} \begin{pmatrix} \text{estimated} \\ \text{noise} \\ \text{power} \end{pmatrix}$$

$$= \frac{V_t^2}{C} - \frac{V_e^2}{C}$$

$$\text{and estimated signal-to-noise power ratio} = \frac{1}{C}\left(\frac{V_t^2}{V_e^2} - 1\right).$$

But the ratio of "between sub-sample variance" to "within sub-sample variance" is the Fisher ratio, which we can call F, so that we have

$$\text{Signal-to-noise power ratio} = \frac{1}{C}(F - 1).$$

We shall make use of this simple relationship after discussing the estimation of signal power in terms of the original data.

In order to visualize correlator functions it is helpful to restate the foregoing

formulae in terms of the original data. To do this, we shall substitute in the expressions for V_t^2 and V_c^2 as follows:

$$V_t^2 = \frac{C}{T-1}\sum_{t=1}^{T}(\bar{x}_t - \bar{x})^2 \quad \text{(between sub-sample variance)}$$

$$= \frac{C}{T-1}\left[\sum_{t=1}^{T}\bar{x}_t^2 + \sum_{t=1}^{T}\bar{x}^2 - 2\sum_{t=1}^{T}\bar{x}_t\bar{x}\right]$$

Remembering that $\bar{x}$ is a constant, one can substitute for

$$\sum_{t=1}^{T}\bar{x}_t$$

the identity $T\bar{x}$. Also, the sum of T squares of averages is equivalent to T times the square of the average, so that

$$V_t^2 = \frac{C}{T-1}\left[\sum_{t=1}^{T}\bar{x}_t^2 - T\bar{x}^2\right]$$

$$V_t^2 = \frac{C}{T-1}\left[\sum_{t=1}^{T}\frac{1}{C^2}\left(\sum_{c=1}^{C}x_{ct}\right)^2 - T\,\frac{1}{C^2T^2}\left(\sum_{t=1}^{T}\sum_{c=1}^{C}x_{ct}\right)^2\right]$$

$$= \frac{1}{C(T-1)}\left[\sum_{t=1}^{T}\left(\sum_{c=1}^{C}x_{ct}\right)^2 - \frac{1}{T}\left(\sum_{t=1}^{T}\sum_{c=1}^{C}x_{ct}\right)^2\right]$$

Similarly

$$V_c^2 = \frac{1}{T(C-1)}\sum_{t=1}^{T}\sum_{c=1}^{C}(x_{ct} - \bar{x}_t)^2$$

(within sub-sample variance, or estimated noise power)

$$= \frac{1}{T(C-1)}\left[\sum_{t=1}^{T}\sum_{c=1}^{C}x_{ct}^2 + \sum_{t=1}^{T}\sum_{c=1}^{C}\bar{x}_t^2 - 2\sum_{t=1}^{T}\sum_{c=1}^{C}x_{ct}\bar{x}_t\right]$$

but

$$\sum_{c=1}^{C}x_{ct} \equiv C\bar{x}_t$$

so that

$$V_c^2 = \frac{1}{T(C-1)}\left[\sum_{t=1}^{T}\sum_{c=1}^{C}x_{ct}^2 + \sum_{t=1}^{T}\sum_{c=1}^{C}\bar{x}_t^2 - 2\sum_{t=1}^{T}C\bar{x}_t^2\right].$$

Since the sum of C averages is equivalent to C times the average, then

$$\sum_{c=1}^{C}\bar{x}_t = C\bar{x}_t$$

and

$$V_c^2 = \frac{1}{T(C-1)}\left[\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}^2 + \sum_{t=1}^{T} C\bar{x}_t \cdot \bar{x}_t - 2\sum_{t=1}^{T} C\bar{x}_t \cdot \bar{x}_t\right]$$

$$V_c^2 = \frac{1}{T(C-1)}\left[\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}^2 - C\sum_{t=1}^{T}\left(\frac{1}{C}\sum_{c=1}^{C} x_{ct}\right)^2\right]$$

$$= \frac{1}{T(C-1)}\left[\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}^2 - \frac{1}{C}\sum_{t=1}^{T}\left(\sum_{c=1}^{C} x_{ct}\right)^2\right]$$

$$\text{Estimated signal power} = \frac{1}{C}(V_t^2 - V_c^2)$$

$$= \frac{1}{C}\left\{\frac{1}{C(T-1)}\left[\sum_{t=1}^{T}\left(\sum_{c=1}^{C} x_{ct}\right)^2 - \frac{1}{T}\left(\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}\right)^2\right]\right.$$

$$\left. - \frac{1}{T(C-1)}\left[\sum_{t=1}^{T}\sum_{c=1}^{C} x_{ct}^2 - \frac{1}{C}\sum_{t=1}^{T}\left(\sum_{c=1}^{C} x_{ct}\right)^2\right]\right\}.$$

Having established the relationship between the Fisher ratio and the signal-to-noise estimate, we can convert the published tables of significance to a form useful in evaluating the capabilities of this correlation process. Figure 2 is a plot of signal-to-noise power versus the sample length, for a five percent level of significance, for 2, 4, 6, 8, and 10 receptors or signal channels. A value read from these curves implies that there is only a five percent probability that the signal-to-noise ratio so observed is due to chance pattern alignments of noise, provided we assume there is no physical basis for noise coherence. Other sets of curves can be plotted for different levels of significance, and will show the possibility of digging deeper into the noise if we accept a higher probability that the estimated ratio arises from chance noise pattern alignments.

In the plot of Figure 2, the time axis is scaled in the number of degrees of freedom in the length of the sample. These degrees of freedom are to be interpreted as independent observations. This means that they must be taken at times sufficiently far apart that the amplitudes observed at one instant do not influence the amplitudes at the next instant. Note that this is not necessarily the rate at which the machine is sampling the data. If the correlator should be sampling more often, one is not entitled to enter the curves with more degrees of freedom; if the correlator samples less often, one should use only its sampling rate in evaluating machine effectiveness.

It is to be noted that the estimates of signal power and of the ratio of signal to noise power obtained by this method depend upon the sample examined. This implies that the estimates can be improved by taking larger samples provided the parameters do not change during the sample period.

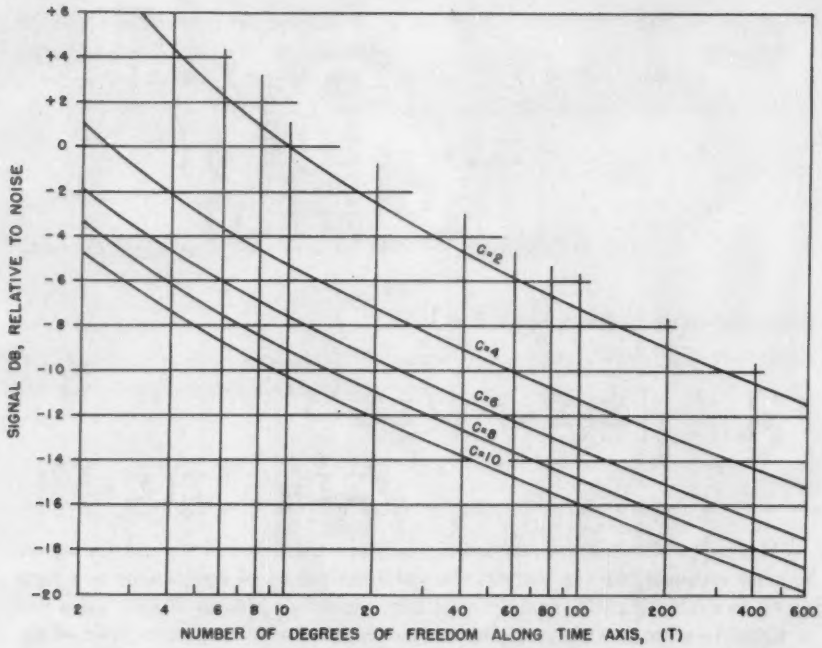

FIG. 2. Signal-to-noise (decibels) versus sample length, for number of channels specified (C), for significance at 5 percent level. Zero db represents equal levels of coherent and non-coherent power.

Finally, if we let ϕ represent the true value of F, we have, from Menzel (1955, p. 111),

$$\text{Mean value of } F = \frac{n}{n-2}\phi, \; n > 2$$

and

$$\text{Mean square deviation (variance) of } F = \left(\frac{n}{n-2}\right)^2 \frac{2(m+n-2)}{m(n-4)}\phi^2,$$

$$n > 4$$

In our present notation:

$$m = T - 1$$
$$n = T(C-1)$$
$$\phi = 1 + CR$$

where

R = true signal-to-noise power ratio.

For large T, we have

$$\text{Mean value of } F \simeq \phi$$

and

$$\text{Mean square deviation of } F \simeq \frac{2}{T}\left(\frac{C}{C-1}\right)\phi^2,$$

so that our estimate, $(F-1)/C$, of the true signal-to-noise power ratio, has, for large T, a mean square deviation of

$$\frac{2}{C(C-1)}\,\frac{(1+CR)^2}{T},$$

and the ratio,

$$\frac{\text{rms deviation of estimated } R}{R} = \sqrt{\frac{2\left(\frac{1}{R}+C\right)^2}{CT(C-1)}}$$

This shows that, for large T and low signal-to-noise ratios, the percentage error of our estimate of the signal-to-noise power ratio is reduced as the number of channels is increased, and in direct proportion.

SOME PRACTICAL RESTRICTIONS

Some statistical procedures, including the analysis of variance, make an implicit assumption regarding the input data which may not be in accordance with the facts about the signals at hand. For instance, suppose we have two or more pure signals, perfectly matching one another in wave form but differing greatly in magnitude because of variations in pick-up effectiveness. The analysis of variance procedure will then yield a number indicating low significance. The analysis is not at fault, but we have an answer which is not as large as we will obtain by equalizing the effectiveness of the pick-ups before starting the analysis. Fundamentally, the statistical process is designed for numbers which reflect factors of standard deviation from a mean. Therefore, we should take steps to insure that our pick-ups are equally effective with respect to the coherent information.

Many analysis procedures, including the analysis of variance are based on the assumption that the amplitude distribution of the input data values is close to normal. With reference to signals, this means that a plot of the frequency of occurrence of each ordinate of any given amplitude shows a distribution which approximates the curve given by

$$y = \frac{N}{\sigma\sqrt{2\pi}} \exp - \frac{x^2}{2\sigma^2}$$

where

σ is the r.m.s. value (standard deviation),

N is the number of ordinates,

x is the measurement of deviation above or below the mean, in terms of the standard deviation.

A mixture of many sine waves of various amplitudes, frequencies and phase angles will approach this normal distribution, but a single sine wave has an entirely different distribution curve, shaped like a U. However, the analysis is predicated only on what we have been calling the non-coherent noise, so, unless that noise band is very narrow, the analysis will remain valid.

Except for the comment in the paragraph immediately above, the effect of limiting the bandwidths has not been considered. Such limitation may become quite important in the application of statistical processing to a signal and noise combination. It is generally true that the signal sampling process, if not continuous, should be at a somewhat higher rate than the highest frequency in the signal of interest. However, the statistical processes under discussion are based on the assumption that no single value in the original data is dependent upon the value immediately adjacent to it in its own sequence. In terms of signal or noise this means that, by hypothesis, the amplitude of the signal or noise at any instant is not dependent upon its amplitude at the immediately preceding instant of examination. However, in actuality, a restriction of bandwidth introduces a form of auto-correlation, so that signal or noise amplitude cannot change faster than the first derivative of the shortest period in the spectrum, and this period is controlled by any natural or artificial filters through which the energy has passed. Therefore, each entry of the statistical process is not completely independent of previous entries, and the significance of the result can be somewhat less than indicated by the answer obtained when complete independence is assumed.

In those cases where the noise contains frequency components considerably higher than those the signal is known to contain, the sampling frequency of machines employing a discrete sampling process may be limited to a frequency only two or three times the highest known signal frequency. By this means, spurious matching of noise patterns will be reduced.

PRESENTATION OF DATA

While there is no fundamental reason why some auditory scheme of data presentation could not be devised, the discussion here will be limited to visual presentation and recording on the usual paper or film strip media.

The first point to be considered is the required rate of presentation. In many cases the signals to be analyzed will have been recorded in a form suitable for playback, and adequate time can be made available for their analysis and pres-

entation. In such cases the only basic requirement is that the statistical result of each scan of the original signal combination be shown in a position such that it can easily be compared with the results of the other scans. One means of doing this is to record, sequentially, the result of each scan in a "raster" of convenient length on the paper or film strip, as shown in Figure 3. In this figure, the points $P_1, P_2, P_3, \cdots, P_{12}$ represent correlation values obtained at different scans, each scan in itself being integrated over the time of the sample chosen. The time duration of each scanned sample is presumed to be the same, but, in general, this does not mean that the samples of individual signals will begin at the same

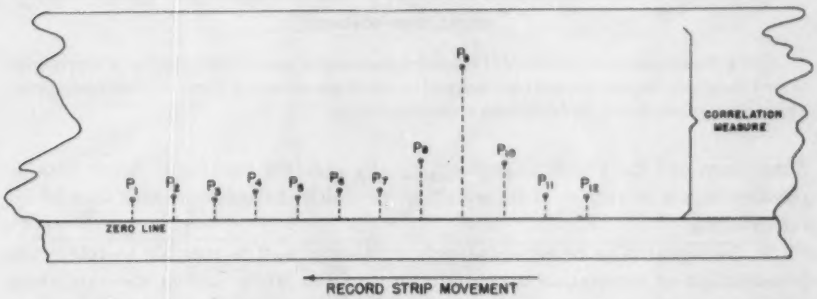

FIG. 3. Presentation of correlation values in a raster. Each value, P_1, P_2, etc., has been time-integrated over the chosen sample length. The dashed lines are drawn to represent ordinates taken at different scans. The height of each ordinate is a measure of correlation between the several input signals. The entire raster represents only one sample, bracketed in time.

instant and end at the same instant. The adjacent ordinates are presumed to have been derived from scans so oriented in relative time that the improvement in correlation follows the gradual improvement in coherence of the signal field as the successive scans are made. This is not a fundamental requirement, but only a logical design to ease the mental effort necessary to understand the presentation.

Figure 4 shows several compressed rasters, successive in time. Here the ordinates are represented by a smoothed curve because ordinary recorders present functions in this manner. The rasters are shown separated for clarity of the figure, although most recorders would draw a continuous line. The raster or time sample numbers shown in the figure are quite arbitrary, but some such arrangement is required if reference is to be made to real time.

The rasters of Figures 3 and 4 have been represented as rather simple forms, such as would be useful for arrays of pick-up devices in only one plane, for a signal field having only one rate of propagation. More complex rasters, or "rasters-within-rasters" would be required for three-dimensional arrays, or arrays taking cognizance of signal fields of different propagation speeds. Essentially, the basic problem is one of representing a magnitude which is a function of a number of

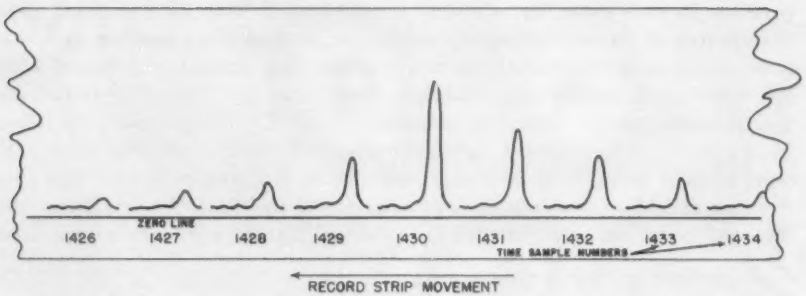

FIG. 4. Presentation of correlation in successive time sample rasters. Here the signal is presumed to have come into the pattern and then dropped in amplitude within the period of time represented. The rasters are numbered, and shown separated for clarity.

dimensions and the practical problem usually involves packing as much data as possible into a minimum of recording space which is consistent with ease of interpretation.

If the signal is to be expected only occasionally, it is possible to retain the presentation of correlation amplitude information while folding the axis along which successive rasters are presented. Figure 5 illustrates such a presentation. This is a good representation because the observer quickly detects a wavy pattern which is of the same general form for successive rasters, which is the pattern produced by one or more signals persisting through several sampling periods. Here the observer's brain actually performs a correlation of the correlograms. However, this implies only that one is more sure of the signal because it persists for several sample periods; or, alternatively, that for this particular signal it would have been better to have the machine look at a larger time sample.

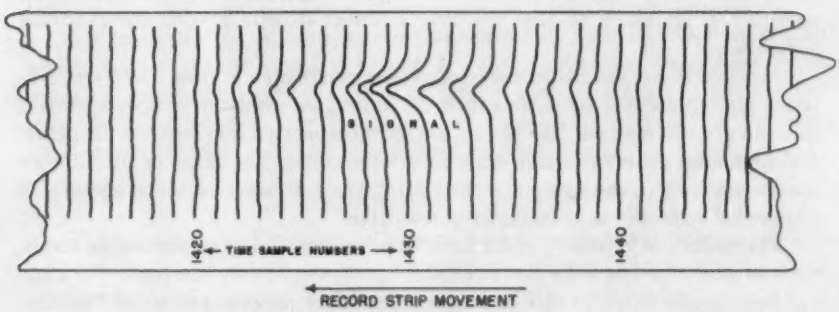

FIG. 5. Presentation of successive rasters on a folded recording axis. The curves of Figure 4 have been nested. Correlation amplitude is shown as increasing to the left. Successive rasters proceed toward the right. The time sample numbers provide an approximate time scale.

In certain instances it may be adequate to have a density presentation of each correlation value in lieu of a position or ordinate presentation. Specifically, if a "threshold" value of correlation can be set, below which one arbitrarily makes the decision that the signal does not exist, then we need only two values of density which can be represented by a mark versus no-mark. Though such a procedure may seem crude, a condensed pattern so constituted can in fact yield the information very effectively. The average density of the pattern areas will often build up in regions outside of those representing the most favorable scans, be-

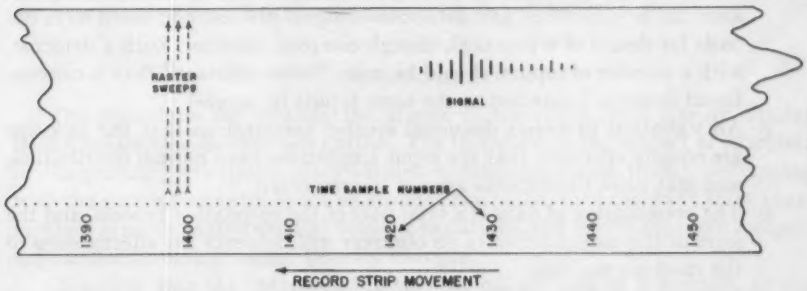

FIG. 6. Presentation of significant correlation only. Rasters are vertical. During the sweep of a raster, the recorder prints only when correlation is above some chosen level of significance. This record can be made much more compact than that of Figure 5.

cause the better signal-to-noise ratios will not require the most favorable scans in order to produce a mark. The threshold system can be made particularly useful in connection with analysis of variance processing because the number computed by the machine is one which, by comparison with a table, determines that some chosen level of significance is or is not exceeded. Therefore, making the recorder print a mark only when this level has been exceeded will give all of the information required to reach a decision on the existence of a signal. Figure 6 shows a possible presentation.

CONCLUSIONS

Defining correlation as a process of matching two or more signals, we have pointed out the following:

1. Any one of several calculation processes may be used to obtain a measure of correlation, the choice being dependent upon the case at hand and the type and quality of result desired.
2. No correlation process, when completed, yields a signal in its original form. All such processes must yield answers which are integrated over some definite length of sample.
3. The processes outlined are not restricted to the pairing of signals and do not involve multiplication of one signal ordinate by another.

4. Of the processes outlined, the sign-coincidence method offers a simple means of dodging the dynamic range problem, at the price of dropping some of the information in a given sample.
5. The analysis of variance processes can yield answers in terms of statistical significance, signal-to-noise ratio, or coherent signal power.
6. For large time samples at low signal-to-noise ratios, the analysis of variance yields estimates of this ratio whose percentage error varies inversely as the number of input channels.
7. The measurement of coherent power obtainable through analysis of variance can be considered as a detection-of-signal process, and could form the basis for design of a practical, though complex, detector. Such a detector, with a number of inputs, should be more "noise-resistant" than a conventional detector connected to the same inputs in parallel.
8. All statistical processes discussed involve assumptions that the pick-ups are equally effective, that the input amplitudes have normal distribution, and that noise bandwidths are not too restricted.
9. The presentation of data is a vital part of the correlation process, and the form of this presentation to an observer will influence the effectiveness of the machine process.

ACKNOWLEDGEMENTS

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GEOPHYSICS, VOL. XXII, NO. 3 (JULY, 1957), PP. 589-609, 16 FIGS.

DESCRIPTIVE GEOMETRY AND THE OFFSET SEISMIC PROFILE*

JOHN P. GATES†

ABSTRACT

An illusion is created in attempting to portray steeply dipping seismic data by standardized geometric procedures. The offset seismic profile, although resembling the vertical geologic cross-section in appearance, may have an inherent tilt which is a function of cross-dip. Unless this tilt is accounted for during the solution of critical structural problems, serious errors can enter into the interpretation of the seismic data. Descriptive geometry procedures are applied to establish the tilt and determine its effects on fault traces, structural axes, and well ties.

INTRODUCTION

The procedures for locating the origins of reflections from steeply dipping beds have become more or less routine. The literature on the subject of offsetting or "migrating" reflections offers various systems to choose from, commencing with the simple lever arm based on straight ray paths, then the wave front chart in which is incorporated vertical velocity variations, and finally the more complex approaches involving lateral velocity changes.

Offsetting may take place during the original plotting of reflections, or the original plot may be *in place* beneath the shot point and an offset profile constructed as a later step. If cross-spreads are employed at the shot points, reflections arriving at a common time from the two directions may be used for a true dip resolution and the resolved reflection offset up-dip to the true origin. Since the profile direction frequently does not correspond with the dip direction, a map view of this offsetting is required in order to adequately portray the direction and distance of offset, as well as the correct depth and dip of the reflecting bed. This may be accomplished by means of strike-dip symbols properly located, with depth and dip values noted. If cross-spreads are not employed, only the component of offset in the profile direction can be determined during the original computing and plotting, and the total offset is then later determined by offsetting the values on the contour map. A twofold purpose is common for all of these procedures, namely to associate seismic reflections as closely as possible with their physical sources, and to portray the seismic data in a form comprehensible to geophysicist and geologist and adaptable for use in geologic structural interpretations. Specifically, the offsetting procedure locates the reflection source and the seismic profile and map portray the data for further application.

Most of the literature regarding offsetting terminates at this point and the assumption can easily be made that from here on the seismic data can be handled directly as geologic data and that the offset seismic profile might be considered the same as a geologic cross-section. Wells could then be plotted on the profile,

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geologic markers located, and geologic horizons projected, guided by the seismic data.

When this assumption is followed however, occasional difficulties arise in making ties between wells and locating faults and structural axes, even though the seismic data appear reliable. It is the purpose of this paper to show that certain of these difficulties can be attributed to a basic difference between the seismic profile and the geologic section, and that the difficulties can frequently be resolved by means of descriptive geometry.

GEOLOGIC SECTION VS. SEISMIC PROFILE

By definition, a geologic section represents a vertical plane taken through the earth's surface. The line of intersection of this plane with the surface is called the line of section and the bearing of this line orients the section. The dip of the beds seen on the section is the total dip if the line bearing coincides with the direction of dip. If these two directions do not coincide what is seen is the apparent or component dip measured in the line direction.

The offset seismic profile also shows component dip in the line direction but, in acquiring the seismic data for this profile, reflections are used which do not necessarily lie within the vertical plane beneath the line of profile. The distance outward from the vertical plane at which these reflections may originate is a function of the amount of cross dip, or component dip measured at right angles to the line of the profile.

Also, slant times from the surface to the points of origin are used to compute depth. The slant component in the direction of the profile is accounted for in the plotting of the profile, but the slant in the direction of cross dip is not. The result is a plot in which reflections appear somewhat deeper than their true depth. For analytical purposes the seismic profile is considered as a tilted plane that has been rotated into the vertical for presentation.

Figure 1 represents a vertical cross-section through an area of relatively steep dip typical of the south flank of an offshore anticline in southern California. The cross-section is taken in the true dip direction. It shows the origins of reflections from a single shot returning to a detector at the shot point. Reflection energy travels along ray paths which may be curved to some extent by velocity variations, but which are perpendicular to the faces of the reflecting beds at the points of reflection. The ray paths are inclined opposite to the direction of dip. The degree of inclination is primarily a function of dip although it is somewhat modified by velocity variations.

Since Figure 1 represents a vertical cross-section taken in the direction of dip, and since the ray paths also occur in this direction, they are seen in their true positions with correct length and inclination.

The geometry of these ray paths is expanded in Figure 1 by connecting all reflecting points with a line representing the *locus of reflections*. This line is important in this discussion as in effect it fixes in space the seismic profile from a

single shot to an adjacent detector. It is seen that the locus of reflections is affected only slightly by velocity variations and curved ray paths, but is highly sensitive to dip changes within the section. It will not follow any individual ray path if velocity or dip variations exist. It may be broken at abrupt dip changes such as at unconformities or faults or may separate into two loci under synclinal conditions.

In order to further expand on the locus of reflections a routine seismic line is visualized commencing at the shot-detector location shown on Figure 1 and extending at right angles out of the dip profile. This would be a strike profile seen in end view in Figure 1. The locus of reflections becomes the end view of a tilted surface which contains all of the origins of the reflections plotted on the strike profile and which intersects the ground surface at the line of profile. It is important to note that the tilted surface is not a locus of ray paths. It will not contain any individual ray path when dip and velocity variations exist and, as expressed by the locus of reflections in Figure 1, it may be broken by abrupt dip changes or be separated into two or more surfaces under synclinal conditions.

Under the unique condition of constant dip and constant velocity the surface becomes a plane. For simplicity these conditions have been assigned in developing the working hypothesis. This plane is referred to herein as the *plane of reflections*.

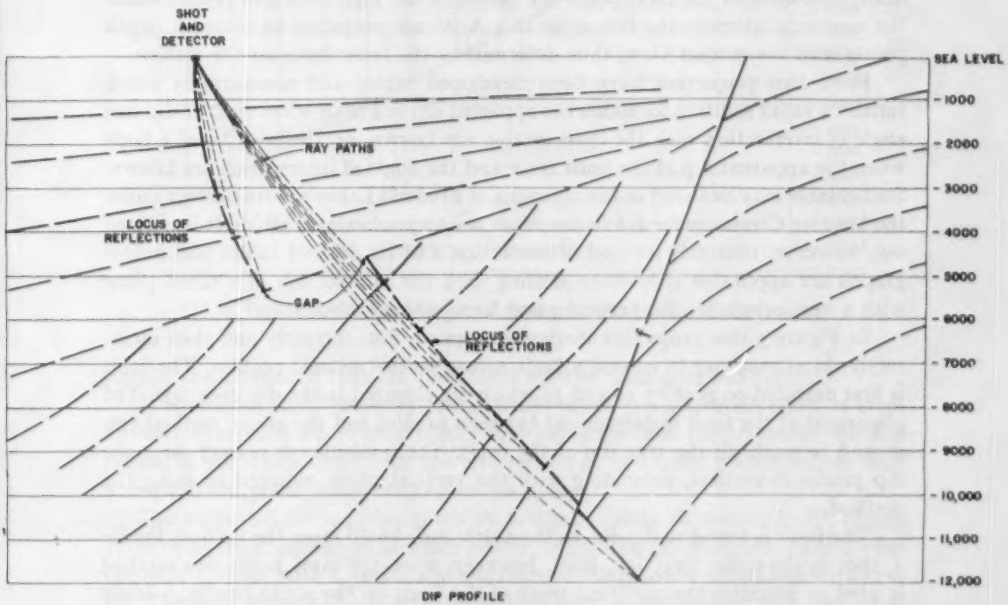


FIG. 1. Ray paths and locus of reflections from a single shot, returning to a detector at the shot point.

It is also used in a broad sense to include the warped and irregular surface resulting from dip and velocity changes in the same manner that the term *fault plane* is used to include curved and warped fault surfaces.

The plane of reflections in essence is the seismic profile. It has an inherent tilt which is a function of cross dip. The tilt is maximum when the profile is oriented in the strike direction and zero when oriented in the dip direction. The dip profile is a true vertical cross-section matching the geologic section but profiles shot in any other direction will not match the geologic section because of the tilt. The degree of tilt can strongly affect the appearance of the profile and the determination of structure.

When some degree of three dimensional control has been obtained, the attitude of the plane of reflections can be determined. The geometry of this plane can then be included in the solution of critical structural problems requiring the fullest use of the seismic data. The following figures show instances where the tilt of the seismic profile becomes important in the solution of the structural problem.

EFFECTS OF CROSS-DIP RESOLVED BY DESCRIPTIVE GEOMETRY

Figure 2 shows the usual projection of a fault plane from a map view to a cross-section. Section A–A′ represents a vertical plane which is intersected by a fault. Contours on the fault plane are shown in the map view and points where the contours intersect the line of section A–A′ are projected as common depth points into the section view, thus determining the fault trace on the section.

From this projection have been developed tables and nomographs which furnish a rapid solution for either the apparent dip of a fault when its true dip and angle of intersection with the cross section are known, or, the true dip of a fault when the apparent dip of the fault trace and the angle of intersection are known. Such a table may be found in the appendix of Frederic Lahee's *Field Geology* under the heading *Correction for dip in directions not perpendicular to strike*. It is pointed out, however, that this method of projection and its derived tables and nomographs are applicable only when dealing with the intersection of a tilted plane with a vertical plane, the vertical plane being the cross section.

In Figure 3 this projection method is applied, first correctly and then incorrectly, in attempting to extend a fault across several seismic profiles. The fault is first detected on profiles 10 and 11 which are oriented in the dip direction. The alignment of the fault is determined between profiles and the above method employed to establish the true dip of the fault. The resolution is correct since the dip profile is vertical, coinciding with the vertical plane required in using the method.

The fault is found to dip 70° to the north and should cross the tie line, Profile 1, shot in the strike direction. Now, however, when the same projection method is used to establish the apparent trace of the fault on the strike profile, a fairly low angle fault trace is plotted which does not coincide with any break in the reflections, implying either that the correlation of fault evidence on the various

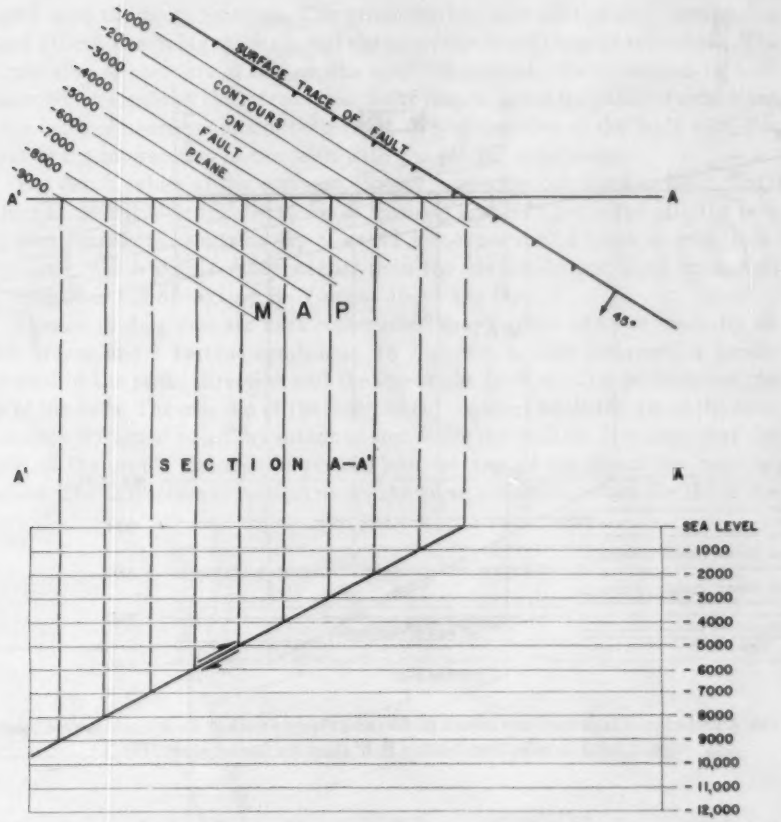


FIG. 2. Typical projection of fault trace from map view to vertical cross section.

profiles is incorrect or that the projection method used does not apply.

It is recalled that the strike profile is subject to the maximum effect of cross dip and is therefore likely to be tilted. Such being the case, the projection method needed is one which deals with the intersection of two tilted planes, rather than a single tilted plane and vertical cross section.

The suspected tilt is investigated by means of (vertical) section B–B′, Figure 4, taken at right angles to the strike profile, i.e., in the dip direction. In this view the beds are seen with true dip and the trace of the plane of reflections with true tilt. The fault trace is also plotted on section B–B′ as determined from the intersection of the fault and section B–B′ in the map view of Figure 3.

It is noted in Figure 4 that all of the source points of reflections at the B–B′

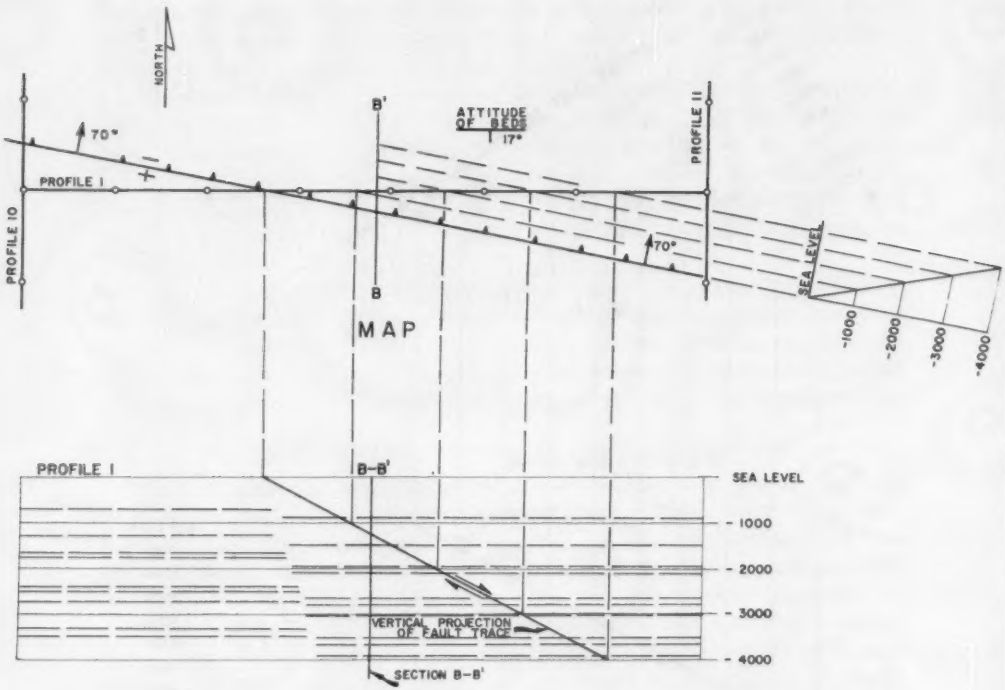


FIG. 3. Projection of fault trace into seismic profile using Figure 2 method. Fault trace does not coincide with break in reflections. Section B–B′ taken for further study (Fig. 4.)

location occur above the fault trace whereas on the profile a major portion of the reflections occur below the originally projected trace. Furthermore, since the fault does not intersect the plane of reflections, it follows that the profile should be unfaulted at the B–B′ location.

This view also shows the method of conversion from vertical depths such as at contour intersections to slant depths conforming with the reflection plot. In this case a constant velocity is assumed, and an arc is swung from the point within the plane of reflections, using the ray path to that point as the radius, to the vertical plane where a new depth is established. In applying this method to actual cases velocity variations can be accounted for by using the reverse of the established offsetting procedure. The ray path and the arc of rotation are thereby modified to fit the wave front chart in use.

Profile 1 is reconstructed in Figure 5. Now, however, contours on the plane of reflections shown in section B–B′ have been added and these contours inter-

sected with the fault contours. The geometry becomes that of two intersecting tilted planes, one being the fault and the other the tilted plane of reflections. The intersection of contours of like depths establish control points common to both planes which establish the intersection of the planes. Since the plane of reflections is the locus of source points of reflections, the intersection of the fault with this plane is the intersection of the fault with the plotted reflections.

The depth values at the common contour points are corrected to slant depth values as described in the discussion of Figure 4 and then projected into the profile where it is found that the new fault trace does occur at a break in reflections. The new trace is considerably steeper than the previously projected trace, and all reflections cut by section B–B′ occur above the fault.

A series of diagrams are next constructed showing the effect of cross-dip on fault traces under various conditions. In Figure 6 a fault intersects a profile oriented in the strike direction and the dip of the fault opposes in direction the dip of the beds. The true dip of the fault is held constant while the dip of the beds is increased from 0° to 40° by means of composite projections. It is seen that the trace on the profile steepens to vertical and reverses as the dip of the beds increases. The fault trace is vertical under the given conditions when the tilt of the

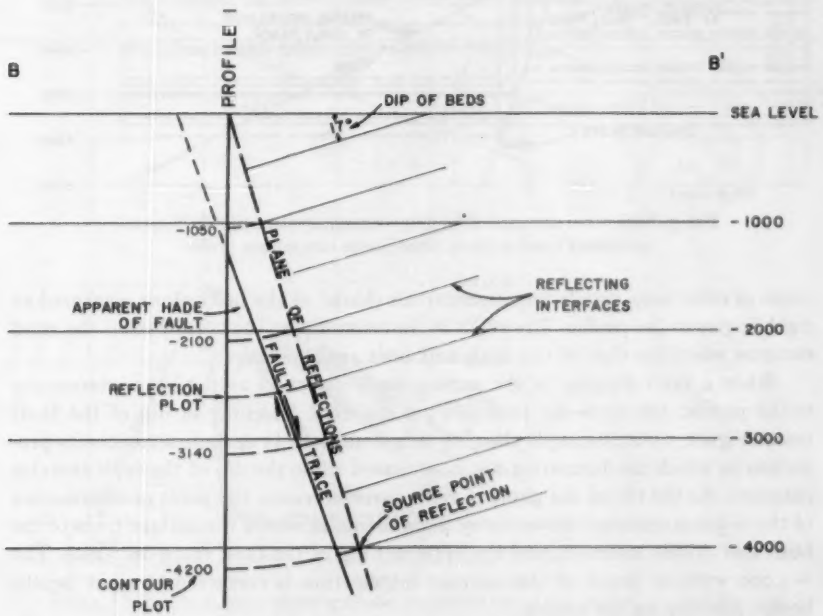


FIG. 4. Section B–B′. Figure 3 projection of fault trace is incorrect as reflections do not intersect fault trace. Plotted reflection depths on profile are deeper than true depth.

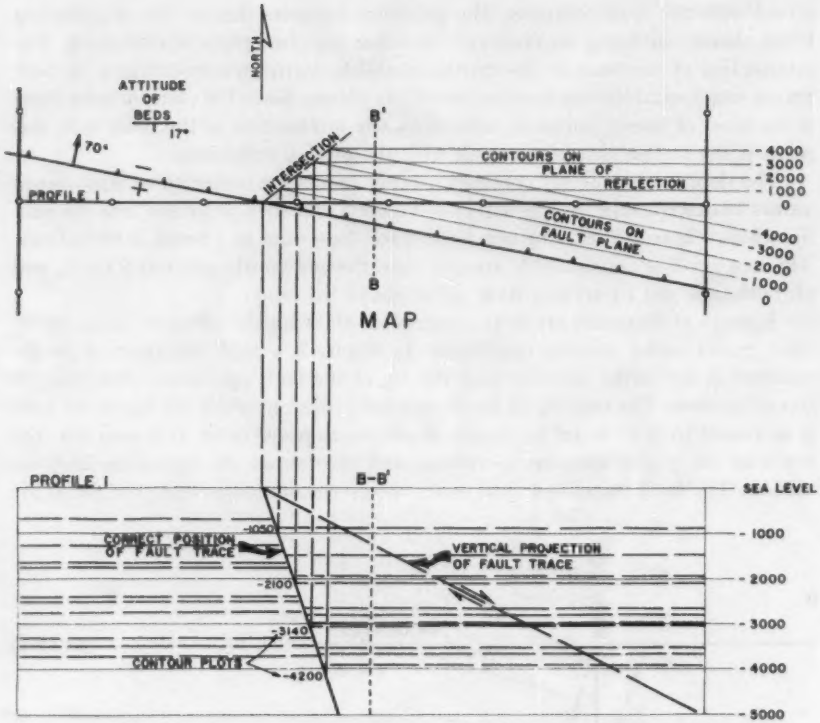


FIG. 5. Fault trace corrected (Fig. 3) by contouring plane of reflections and projecting intersection of tilted planes into seismic profile.

plane of reflections equals the apparent tilt (hade) of the fault plane measured at right angles to the profile. The effect of the cross-dip on the fault trace is the most extreme when the dips of the fault and beds are opposing.

When a fault dipping in the same general direction as the beds intersects a strike profile, the cross-dip produces an apparent lessening in dip of the fault trace. Figure 7 is an example showing this condition. It again is a composite projection in which the formation dip is increased while the dip of the fault remains constant. As the tilt of the plane of reflections increases, the point of intersection of the $-5{,}000$ contours moves away from the point where the surface trace of the fault and profile intersect, and the apparent dip of the fault trace decreases. The $-5{,}000$ vertical depth of the contour intersection is corrected to slant depths before plotting on the profile.

Figure 8 shows a fault at right angles to the strike profile and dipping 45°. The

composite projection this time reveals a slight steepening of the fault trace as the formation dip is increased. The steepening is due entirely to the increasing slant depth at which the contour intersection points are plotted.

On occasion this steepening effect of the slant plots can counteract the shallowing effect occurring when fault and beds dip in the same direction (Fig. 7), and the resulting trace will appear as on a vertical section.

A profile aligned oblique to strike is shown in Figure 9. In this case contours on the plane of reflections are seen not to follow strike but to parallel the line of profile. These contours will remain parallel as long as the amount of cross-component dip remains constant. The contours on the plane of reflections are either constructed from depth points on a strike dip plot of resolved "L" spread data,

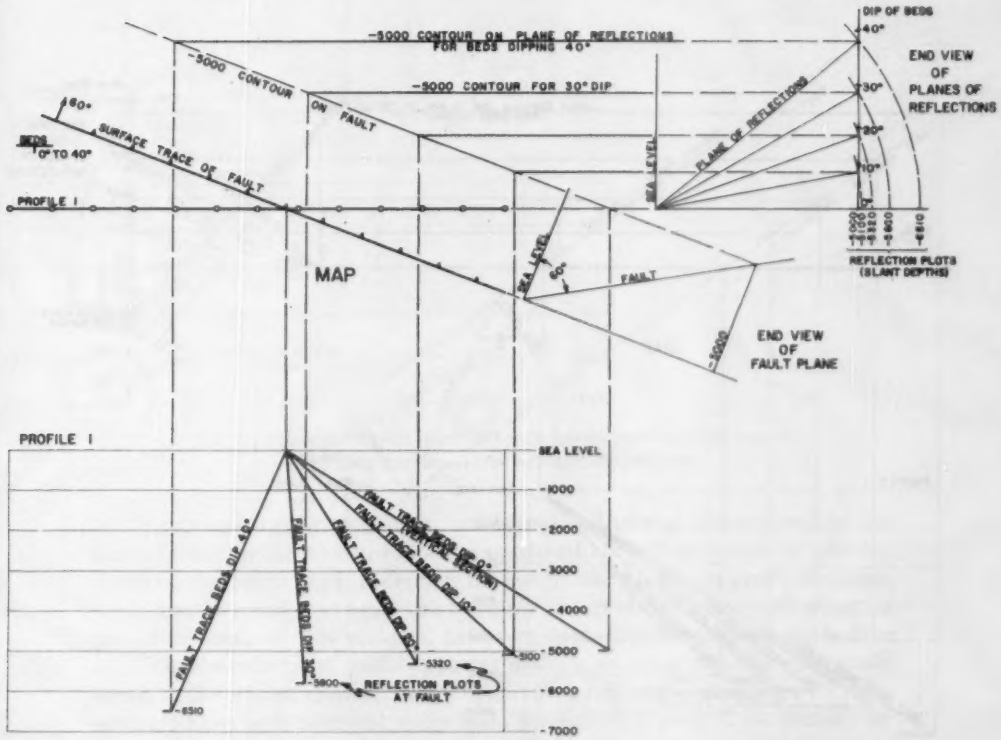


FIG. 6. Composite diagram showing effects on seismic fault trace created by changing true dip of reflections. True dip of fault remains constant. Strike profile. Dip of fault opposes dip of beds. Fault trace steepens and reverses as true dip of beds is increased.

as later described, or from depth values at points on offset contoured horizons. In the latter case, contours would be interpolated between the ground surface and the subsurface points on the horizon.

A method of transferring data developed on the plane of reflections, from the map view to the profile, is shown by means of point A. It is first established as being a point on the −5,000 contour of the plane of reflections. The map view shows the point in its true position, and with true depth. It will occur on the profile directly opposite the point of origin. The ray path to point A is next constructed in the map view. In this case, since velocity and dip are constant, the ray path coincides with the locus of reflections. The amount of offset that point A will have in the profile is next transferred by rotation to the ray path (locus of reflections). By projecting into the true view of the locus of reflections, the angle

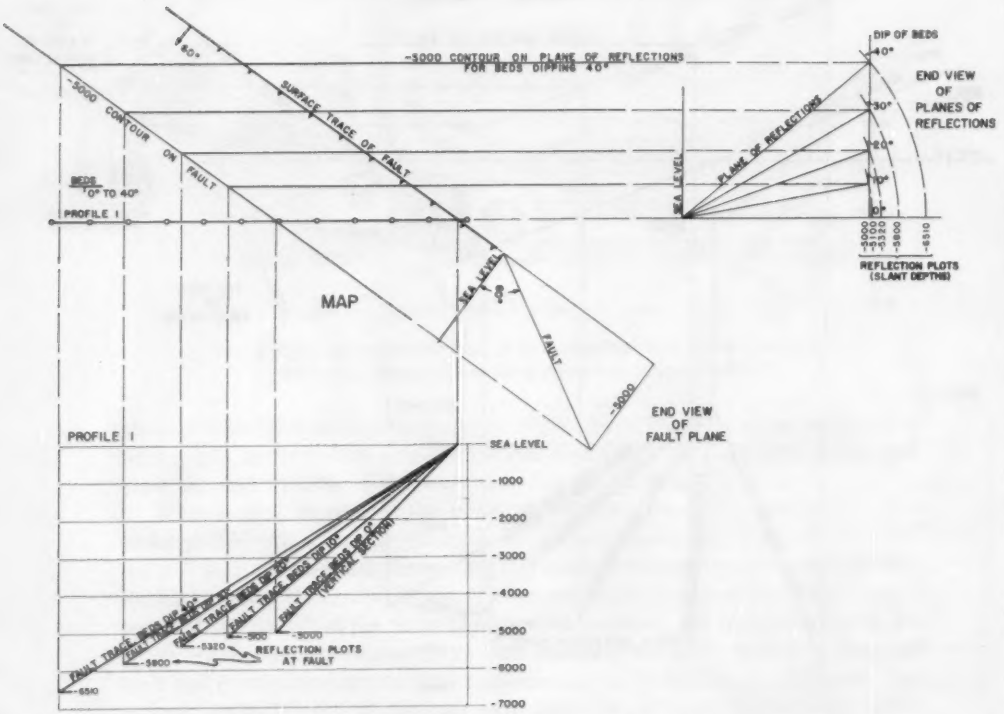


FIG. 7. Composite diagram similar to Figure 6. Dip of fault in direction of dip of beds. Fault trace shallows as true reflection dip increases.

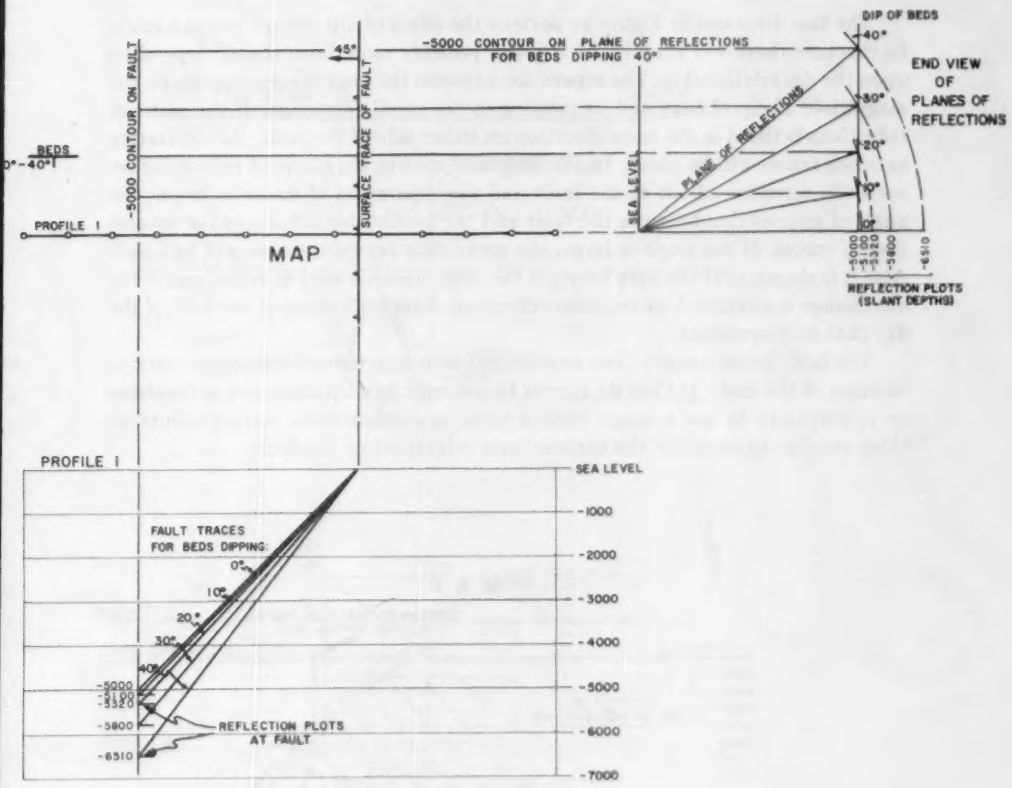


FIG. 8. Composite diagram. Fault intersects seismic profile at right angles. Fault trace steepens as true reflection dip increases.

of tilt required for the total offset can be reduced to that tilt required for the plotted offset in the profile. From the shortened arc is determined the plotting depth on the profile, and, if desired, the component dip in the profile direction.

It may be noted that again this is simply the reverse of a standard offsetting procedure used, on this occasion, to revert data, first determined at the true origins of the reflections, to the apparent position on the profile that they would occur. In the original construction of the profile a reflection coinciding with point A would have been migrated updip from beneath shot point X an amount determined by the component dip in the profile direction. This amount is equal to the "plotted offset" distance shown in the true view of the locus of reflections. The ray path used in the plotting would be seen in true length in the same view.

The two diagrams in Figure 10 portray the effect of dip change across a fault. In this case there will actually be two and possibly more fault traces, depending upon the dip relationship. The separation between the fault traces depends on the magnitude of dip change and its relation to the profile direction. If the plane of reflections is tilted in the same direction on either side of the fault, the separation between traces will be small. In the diagrams shown, the plane of reflections reverses in direction of tilt at the fault and the separation of traces is large. The angle of intersection between the fault and the profile also influences the separation of traces. If the angle is large, the separation between traces will be small. Also it is shown that the area between the fault traces is void of reflections if the dip change is anticlinal, or contains reflections from both sides of the fault if the dip change is synclinal.

The fault traces usually (but not always) converge toward the correct surface location of the fault. If they do appear to converge in such a manner, it furnishes an opportunity to use a single surface point and relate it to surface points on other profiles to establish the surface trace alignment of the fault.

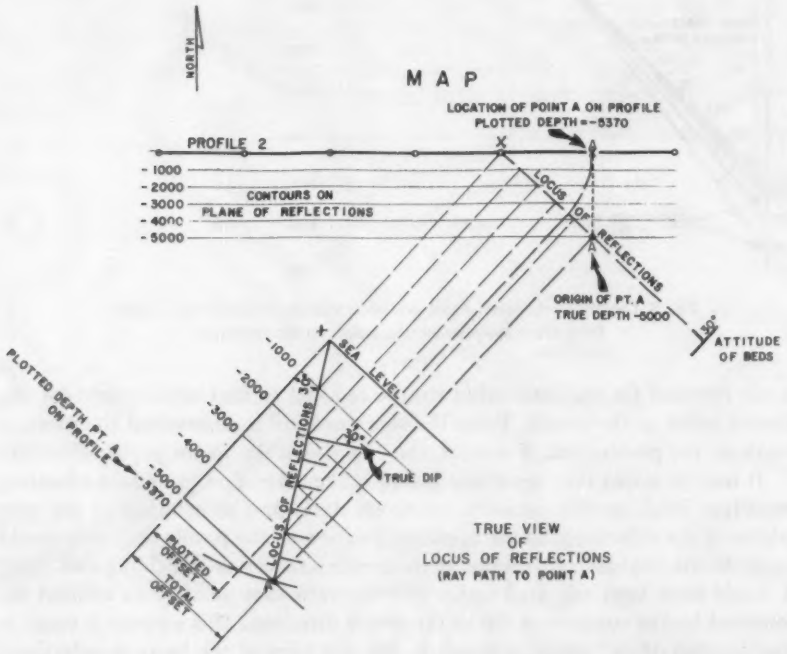
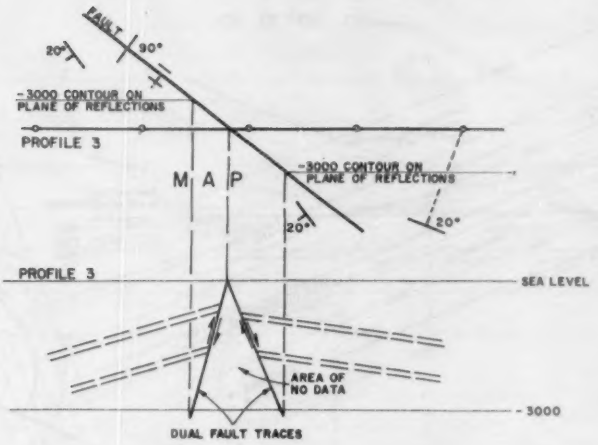
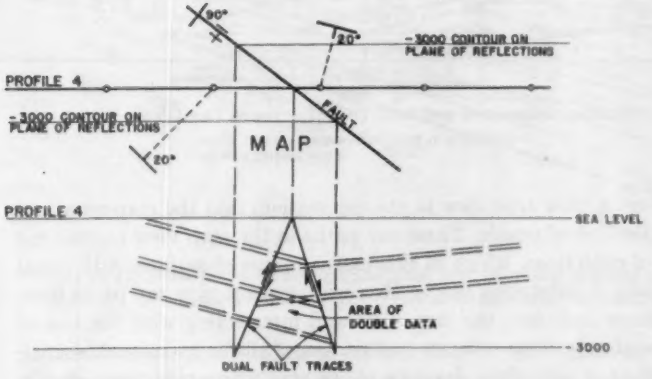


FIG. 9. Profile aligned oblique to strike. Method of transferring point on plane of reflections to plotting position on profile is routine offsetting procedure in reverse.



(A)



(B)

FIG. 10. (A) Dual seismic fault traces created by dip change. Area between traces is void of reflections if dip change is anticlinal. (B) Area between fault traces contains reflections from both blocks if dip change is synclinal.

When folding is associated with a fault, the geometry of the seismic profile may become somewhat involved. An example of a faulted anticline is shown in Figure 11, as it might appear on a seismic profile taken obliquely across the structure. The dip section at the right side of the figure shows the anticline in true cross section. The structure is assumed to have no plunge in either direction, therefore the horizon contours are drawn parallel. Under this condition ray paths

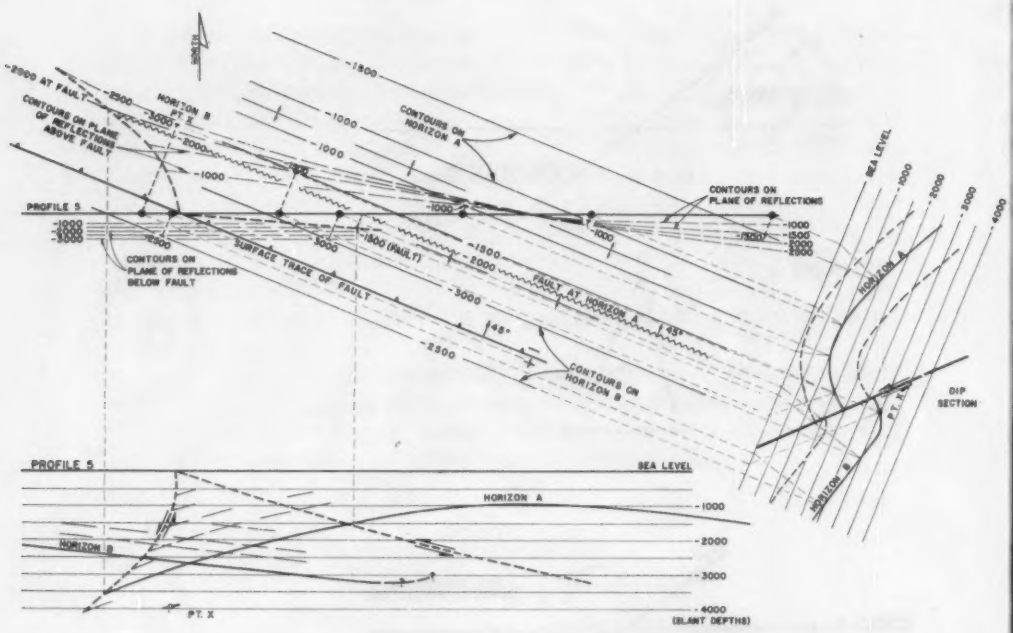


FIG. 11. Structural deformation and fault. Dual fault traces. Overlapping reflections in synclinal area.

can be projected from their true view in the dip section, into the map view and intersected with the line of profile. These ray paths in the map view control the tilt of the plane of reflections, which in this case is a curved surface. Additional control on the plane of reflections can be obtained by projecting ray paths from shallower and deeper beds into the map view and intersecting with the line of profile. The plane of reflections reverses in direction of tilt as it crosses the anticline. A second plane of reflections develops in the area where reflections are obtained from below the fault. Both planes of reflections intersect the fault plane and two fault traces result. Since the structure at the fault is synclinal, an overlap of data occurs. Difficulty is encountered in precisely locating the trace terminating the horizon B reflections because of upturn just below the fault. Point X, shown in the dip section as being on the upturned end of the horizon, is apparently on a third plane of reflections on which there is insufficient control for mapping. In the plane view, point X originates north of the profile rather than south as do the majority of horizon B reflections, and in the profile this point occurs some distance away from its expected position at the upturned end of

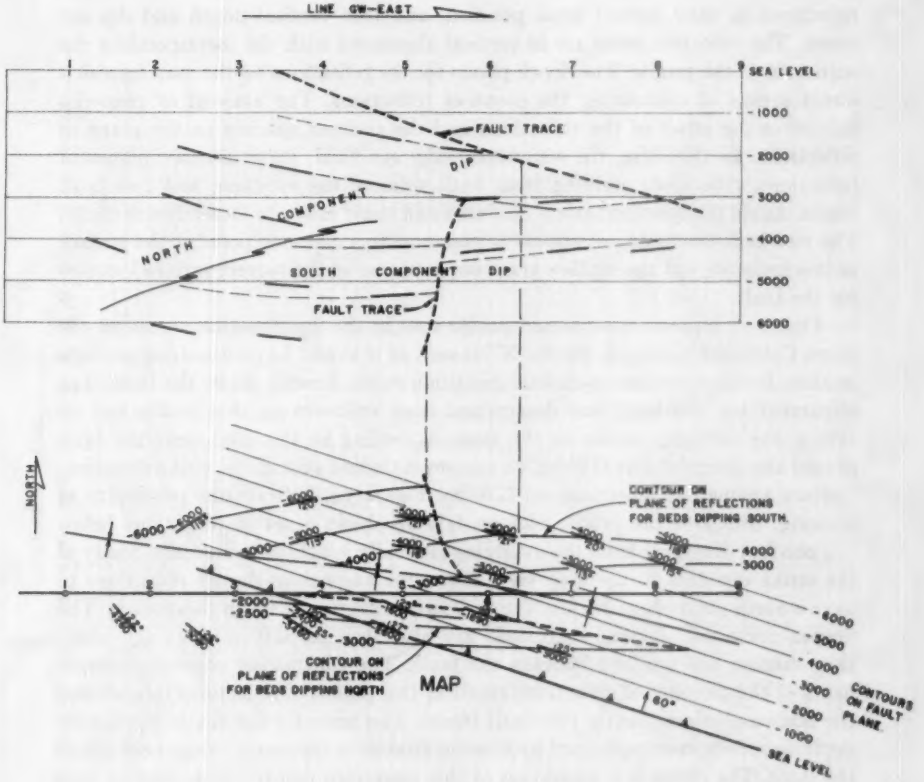


FIG. 12. Profile across faulted syncline. Dual fault traces and obscured synclinal axis. Map view shows typical plot of offshore strike-dip data.

horizon B. Attention is called to the fact that the anticlinal axis is seen at its correct location in the profile aligned oblique to structure, but that the synclinal axis is obscured by the overlapping data. If a portion of the overlapping data were ignored as being invalid, the synclinal axis might be erroneously located at the beginning edge of the double data, and the flank of the anticline falsely extended.

A seismic profile crossing a faulted syncline is seen in Figure 12. The illustration was drawn to conform with the typical plot of L spread data used in the offshore work in California. A map view is drawn at the bottom of the profile with the shot points on the map in vertical alignment with the shot points on the profile. Strike dip symbols are plotted on the map, signifying the origins of the

reflections in their correct areal position, and true vertical depth and dip are noted. The reflection plots are in vertical alignment with the corresponding dip segments on the profile. The depth points for the reflections on the map furnish a direct means of contouring the plane of reflections. The amount of cross-dip influences the offset of the reflections and the contour spacing on the plane of reflections. In this case, the structure being synclinal, there are two planes of reflections, reflections arriving from both sides of the syncline, and two fault traces. Again the synclinal axis is obscured and could easily be located incorrectly. The two fault traces do not appear to converge to a common point at the surface in this instance, but the shallow trace does outcrop at the correct surface location for the fault.

Figure 13 represents an actual profile shot in the dip direction across an offshore California anticline. Fault "X" is seen as it would be on a normal geologic section. It is noted that a synclinal condition exists directly below the fault. The alignment for this fault was determined from evidence on this profile and on GW-3, the next dip profile to the west. According to this alignment the fault should also intersect line GW-29, an east-west tie line shot in the strike direction. Certain anomalous reflections on GW-29, Figure 14, indicate the possibility of faulting. Study of the profile plot on GW-29 shows a set of reflections below −4,000 feet diverging from the overlying generally synclinal main body. Study of the strike dip data in the map view shows the anomalous deeper reflections to have a north component dip and the shallower reflections a south component. The deeper northeast dipping reflections are also seen on GW-2 (Fig. 13) where they disclose the syncline beneath the fault. The contrasting cross-dip components of the two sets of reflections result in two planes of reflections intersecting the fault and consequently two fault traces. The trace for the south dipping reflections is further complicated by a minor change in the south component dip at the fault. The result is a separation of this trace into two traces around an area of double data. Of interest is the fact that the lower ends of these latter traces fall close to two steeply dipping reflections which obviously do not conform to the dip of the beds, and may possibly be associated with the fault.

Although this fault does not appear to extend to the surface, the fault traces do appear to converge toward a point near the surface location of shot point 60. This point is in good alignment with the projected surface trace of the fault as determined from profiles GW-2 and GW-3.

WELL TIES ON TILTED PROFILES

Another problem relating to the tilt of the seismic profile is that of properly locating well points for use in establishing seismic horizons. Figure 15 shows a seismic profile beginning at a well and proceeding in a direction oblique to dip. A seismic horizon is desired on the top of the "A" zone, which occurs in the well at −10,000 feet. It is known that the dip at the A zone is N. 16° W., 20°. In order to locate a point on the geologic marker which would produce a reflection on the

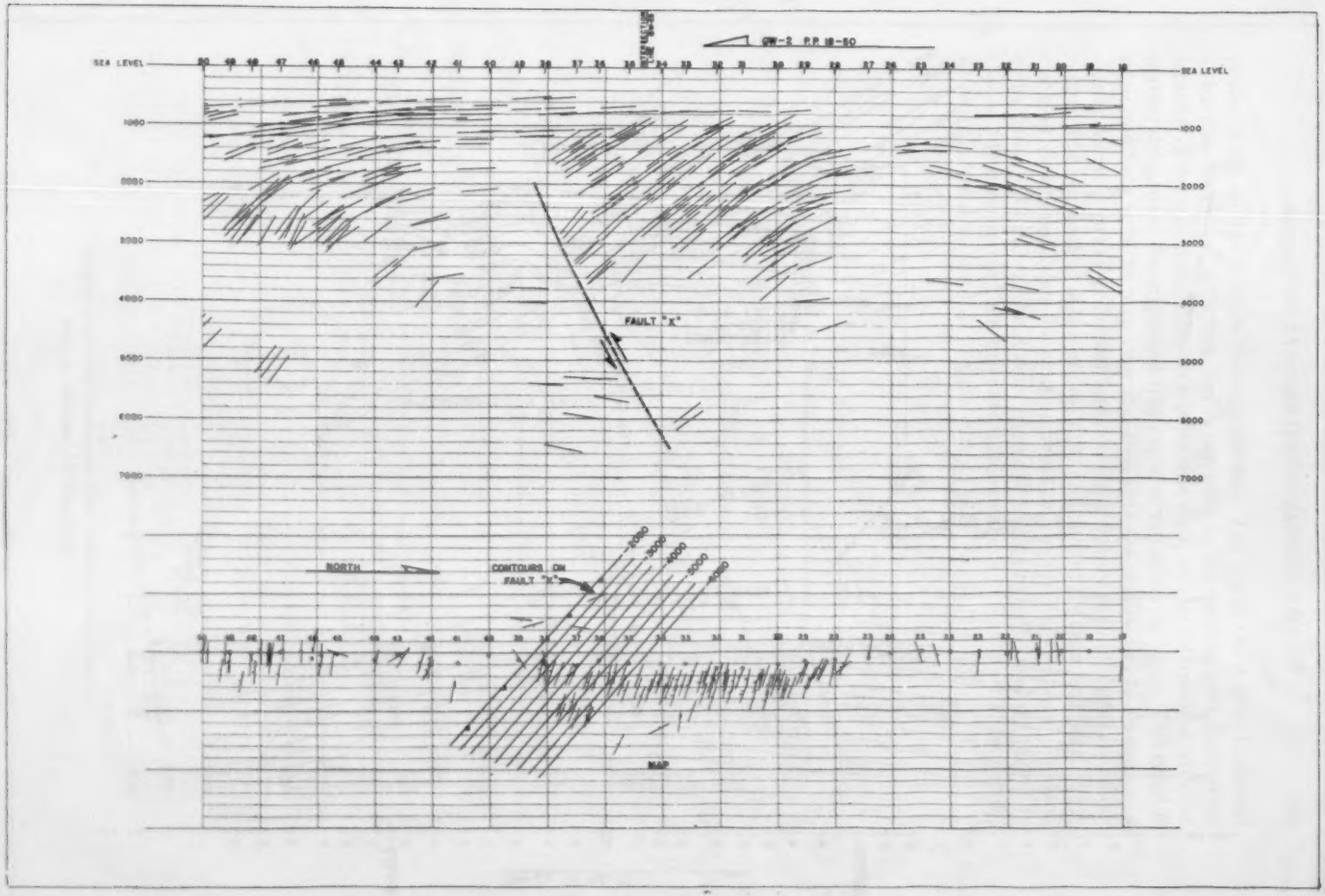


FIG. 13. Fault "X" on dip profile. Offshore California.

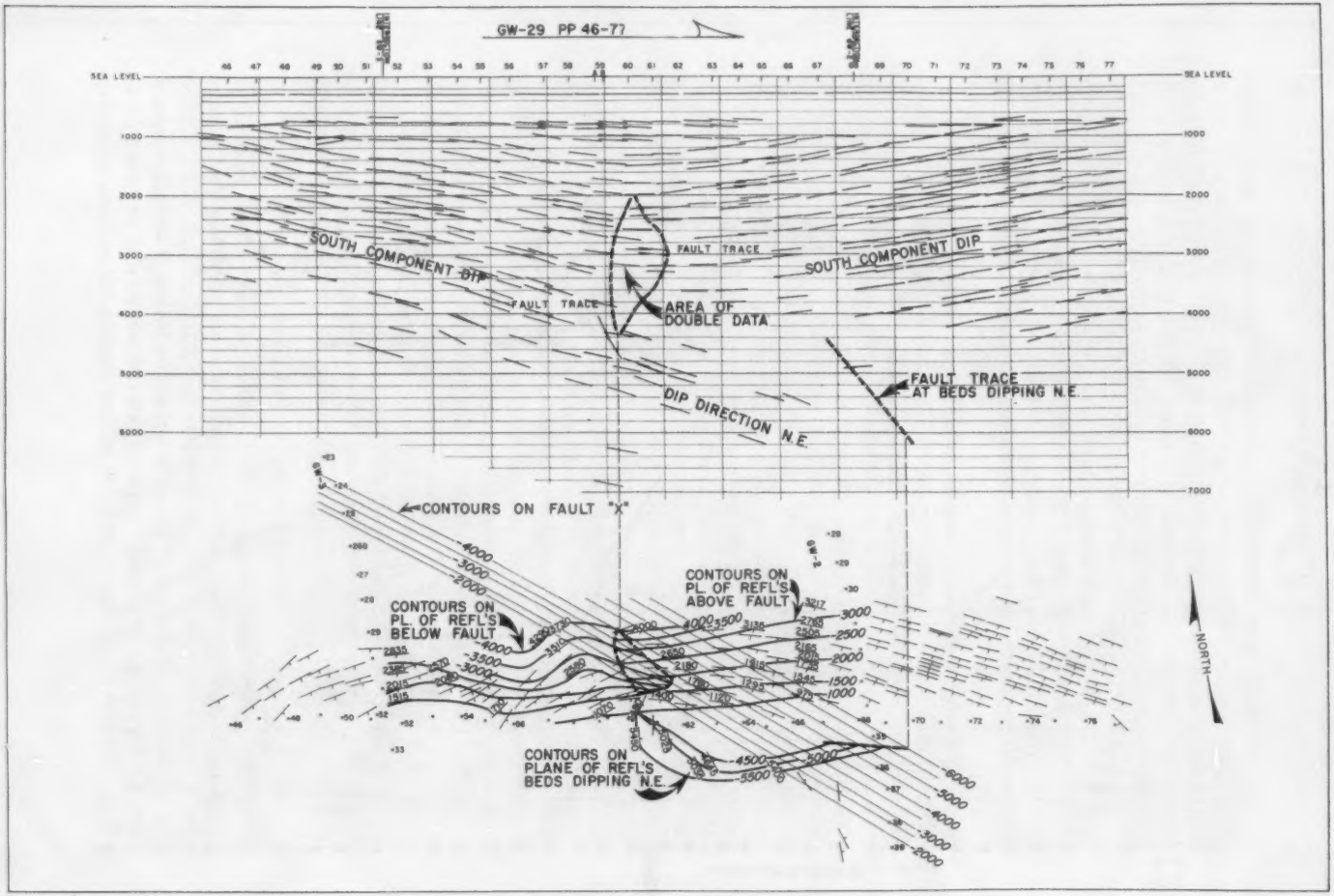


FIG. 14. Fault "X" on strike profile.

profile, a dip section is taken through the well. The top of the A zone is plotted at its true depth and with true dip. A ray path to the marker from the surface location of the well then is also seen in its true view, and its intersection with the marker determines the origin and true depth of the reflection point. This point is projected back into the map view and then into the profile, but to an unknown depth. An arc is swung at the well location using the ray path in full length as the radius. The intersection of this arc with the projector of the reflecting point (from the map view) establishes the plotting depth on the profile. The seismic horizon equivalent to the top of the A zone passes through this point and is tangent to the arc. The horizon is then extended through the well location on the profile, where it is found to occur at −9,480 instead of −10,000 feet.

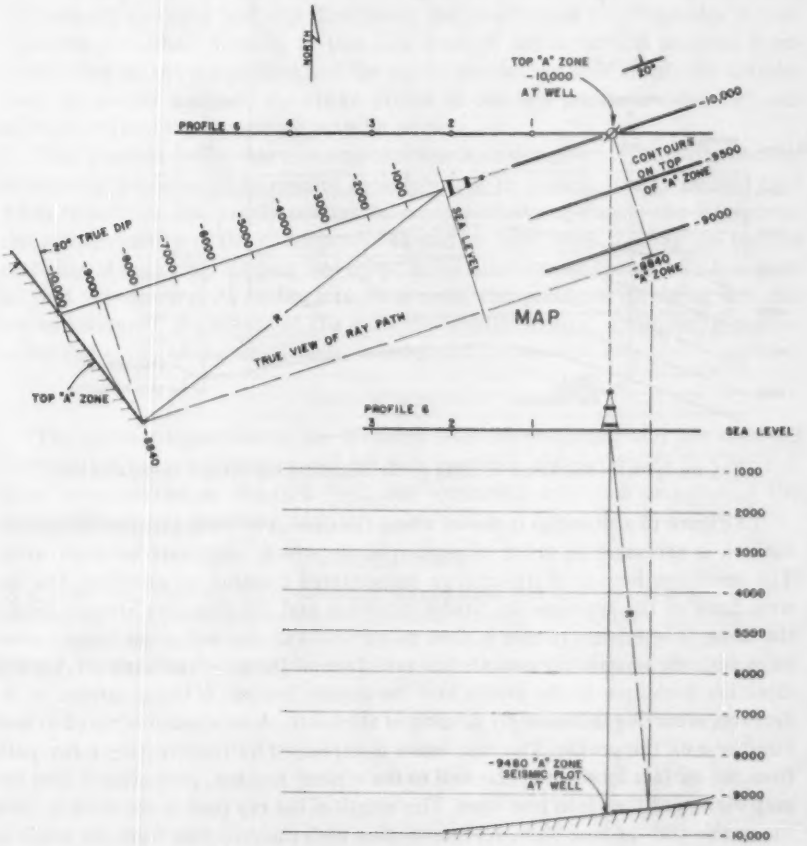


FIG. 15. Location of geologic marker on offset seismic profile. Constant velocity assumed for simplicity.

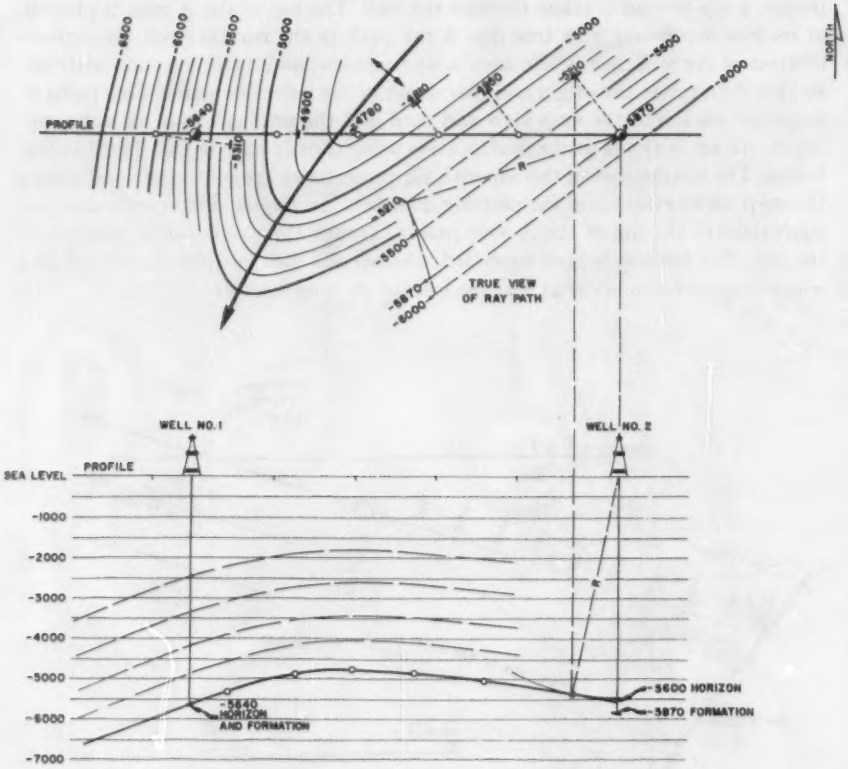


FIG. 16. Apparent misclosure on offset profile created by dip changes across structure.

In Figure 16 a situation is shown where the correct identification of the seismic horizon is necessary in order to explain an apparent misclosure between wells. The condition here is of dip change encountered crossing an anticline. On the west flank of the anticline the profile direction and dip direction are practically the same. The seismic profile is close to vertical and the well point closely coincides with the seismic horizon. On the east flank of the anticline however, the dip direction is oblique to the profile and the seismic horizon is being carried on reflections occurring increasingly distant to the north. A misclosure is noted at well number 2 on the profile. The misclosure is explained by constructing a ray path from the surface location of the well to the seismic horizon, projecting it into the map view, and then into true view. The length of the ray path is the same in both the profile and the true view. Its intersection with the projector from the origin in the true view determines the vertical depth and the total angle of dip. The dip

line is extended to meet the projector from the well, and the vertical depth of −5,870 is obtained. This depth coincides with the depth to the formation at the well and it is evident that there is no misclosure.

DISCUSSION

L. F. Ivanhoe (1955, 1956) has published two excellent articles on the subject of tilted seismic sections. By use of block diagrams he demonstrates various effects of cross-dip on seismic fault traces. He shows how the Meridian stereonet may be used in the analysis, and (1956) he shows how velocity adjustments may be introduced during the projection of well data. These articles are recommended as sources of additional information and methods.

When the opportunity arises for orienting the seismic lines in a grid pattern conforming to strike and dip directions, the problem of tilted profiles is considerably simplified. Usually in this case most of the structural analysis is accomplished on the dip profiles and the strike profiles are used chiefly for correlation. By proper usage of the strike profile in detailed problems however, considerable valuable information may be added.

The question frequently arises as to when does the effect of cross-dip become sufficiently pronounced to require consideration. In general it may be said that when reflections dip steeply enough to require offsetting during the interpretation, the geometry of the tilted profile should be considered. During the routine mapping of uniformly dipping beds, just to be conscious of the tilt effect may be all that is necessary. As faults, structural axes, and problems involving well ties are encountered, the effects of the cross dip become critical and usually require a detailed study of the tilted surfaces involved.

ACKNOWLEDGMENT

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GEOPHYSICS, VOL. XXII, NO. 3 (JULY, 1957), PP. 610–629, 15 FIGS.

ORGANIC REEFS OF PENNSYLVANIAN AGE IN HASKELL COUNTY, TEXAS*

DE WITT C. VAN SICLEN†

ABSTRACT

The reflection seismograph was used to map a prominent organic reef in the Pennsylvanian system near Stamford in central northern Texas, and the results were checked by drilling. Since seismic wave velocity in the limestone comprising the reef is nearly twice that in the enclosing shale, distinctive reflections from beds below the base of the reef were mapped above their true position by an amount equal to almost half the reef limestone thickness. The false structure so mapped has been interpreted as showing the topography of the upper surface of the reef. As such, it is a mound 3 miles long and half as wide, with a corrected height of 1,000 feet and a central depression 300 feet deep, resembling a present-day atoll. Numerous wells confirm the presence of this reef, but cast serious doubt upon the simple topographic interpretation of the seismic map. The atoll-like central depression appears to be an illusion, caused by the reef having a relatively high-velocity shell and a lower velocity center.

The Stamford reef is an exceptional development along a seemingly continuous reef belt mapped similarly with the reflection seismograph for 25 miles. Where reef development is less extreme along this belt, and along two others of a closely related type, the reef trends show up as long, gently curving, somewhat irregular seismic "highs" with many small contour closures. Detailed seismic interpretation of these reefs, and of the structure of underlying horizons which they obscure, must await improved geologic understanding of the reefs and of the subtle changes in lithology that modify seismic wave velocity.

Stamford reef illustrates also what a difference there can be between seismic closure, an obvious trap by subsurface mapping, and the location of a good oil fielld.

INTRODUCTION

An exceptionally well developed organic reef occurs in the Canyon (Missouri) series of the Pennsylvanian system in southern Haskell County, Texas. It will be referred to as the Stamford reef, after the town of that name located 2 miles to the southeast. The Stamford organic reef is a mass of limestone 3 miles long, 1.5 miles wide, and up to 1,000 feet thick, enclosed completely in a shale section more than 2,500 feet thick. The feature was discovered, recognized, and mapped with the reflection seismograph, and explored further with the drill.

The information which follows has been released graciously by the management of Pan American Production Company. This paper was made possible by the careful work of many geologists and geophysicists. The "shooting" was done in 1946–49 by a General Geophysical Company crew under Ural A. Rowe, supervised by T. O. Hall. Their results were reviewed and made the basis of well locations by Pan American geophysicists, particularly former chief geophysicist, O. T. Lawhorn, who took special interest in the Stamford reef and inspired the writer to prepare this paper. Numerous geologists while at Pan American's Abilene district office contributed to the subsurface geological knowledge of the Stamford reef, among them being James R. Day, Ben H. Martin, Wm. B. Rodan, and Jack Hendrickson. Messrs Hendrickson and Joseph D. Watzlavick were especially helpful in assembling material for this paper, in providing information

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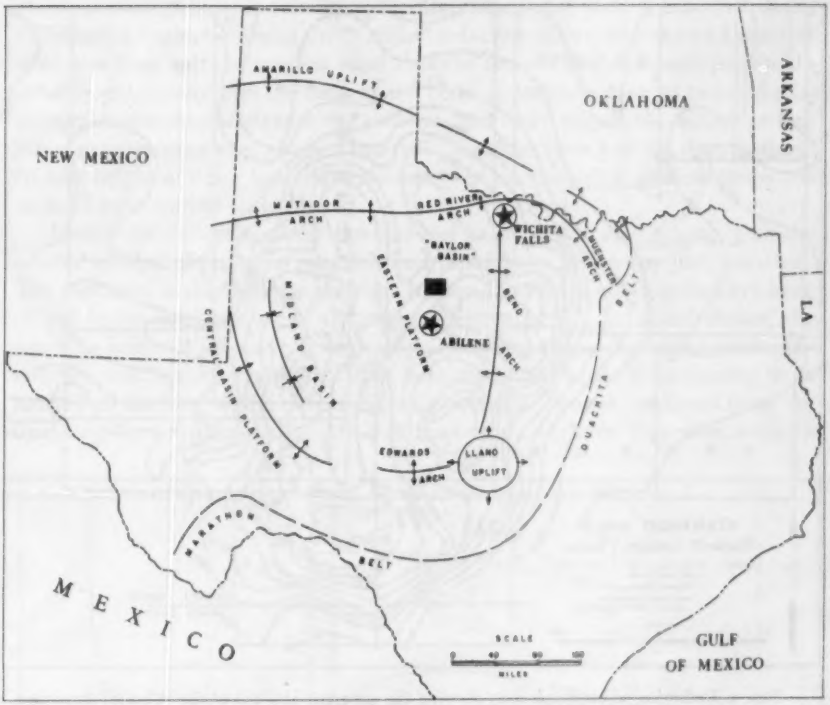

FIG. 1. State of Texas. The black rectangle represents the area covered by the accompanying larger-scale maps, Figures 2, 3, 4, 10 and 11. The area shown on Figure 13 lies 20 miles northeast of the center of the rectangle.

and advice on the problems encountered, and in reviewing the final manuscript. The writer put together the data provided by these men and by company records, and made the interpretations. He assumes full responsibility for all interpretations, particularly those pertaining to reef geology and its effects on seismic work. Illustrations were prepared by Pan American draftsmen Frank Bishop, Charles Beinhorn, and Josef Weber, under the supervision of W. O. Shands. Geologists working for other operators in the area also made substantial though indirect contributions to this paper. The writer is deeply indebted to these many people, unnamed as well as named, for the material which he presents here.

INTERPRETATION OF SEISMIC RESULTS NEAR STAMFORD

The seismograph was able to map the Stamford reef because seismic waves travel through the limestone comprising the reef almost twice as fast as through the shale beside the reef. Consequently, distinctive reflections from the "Caddo" and older limestones 1,200 feet and more below the bottom of the reef were received back at the surface in less time if they passed through intervening high-

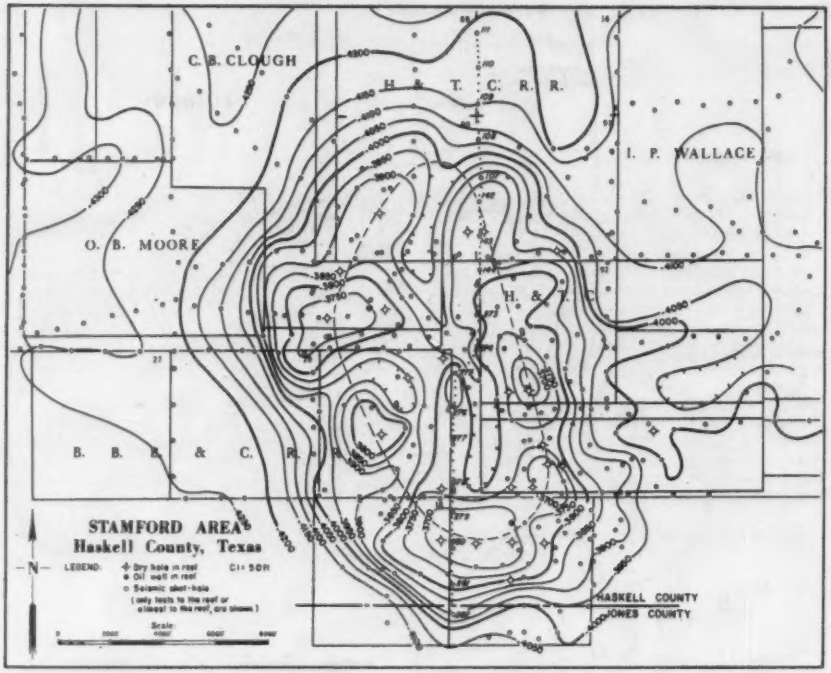

FIG. 2. Reflection seismograph map showing the apparent attitude of the "Caddo" limestone. Dashed line is seismic crest line of reef. Dotted line shows position of Figure 7, a seismic profile. Only wells to top of reef, or almost to it, are shown.

velocity limestone than if they passed through only low-velocity shale. Since depth to a reflecting horizon is estimated from measurements of the time it takes for waves to be reflected back to the surface, the "Caddo" reflection was mapped at a much shallower position beneath the reef than elsewhere.

Figure 2 shows the seismic false structure of the "Caddo," and Figure 3 shows its actual attitude as disclosed by drilling. The difference between the two maps is caused entirely by the high-velocity reef limestone. Since structural relief of the "Caddo" is negligible compared to its false seismic relief, the seismic map is an approximate isopach map of the reef limestone. Since the base of the reef also is about flat, as disclosed by four wells which drilled through the reef (data indicated on Figure 4), the seismic map has been interpreted practically as representing the topography of the top of the reef.

The reef, so interpreted, has the form of a mound with a depression in the center, like an atoll. The rim consists of several hills of slightly different height with valleys between. The valley to the north is especially large, and has a continuous slope which would drain the central depression.

Since average seismic velocity in the limestone is not quite double that in the surrounding shale, the top of the "Caddo" reflection shown on Figure 2 has somewhat less than half the vertical relief that the top of the reef should possess. In other words, to envision the form of the body of reef limestone as mapped seismically, one must redesignate the contours of Figure 2 from the actual 50-foot interval to an imaginary 100-foot interval. Then the limestone hill rises to about its true height of 1,000 feet above the base and the central depression drops 200 to 400 feet below the enclosing rim.

Most wells drilled into the Stamford reef have been located primarily on the seismic work, interpreted as reflecting reef topography in the way just described. The reef form as disclosed by the wells is shown in Figure 4. No wells have been drilled in the deeeper part of the central depression and its outlet toward the north to prove or disprove their reality. However, the wells drilled inside the seismic crest line, which should have been somewhat lower than nearby wells located on the rim, either were not nearly as much lower as predicted from the foregoing topographic interpretation of the seismic work, or they were actually

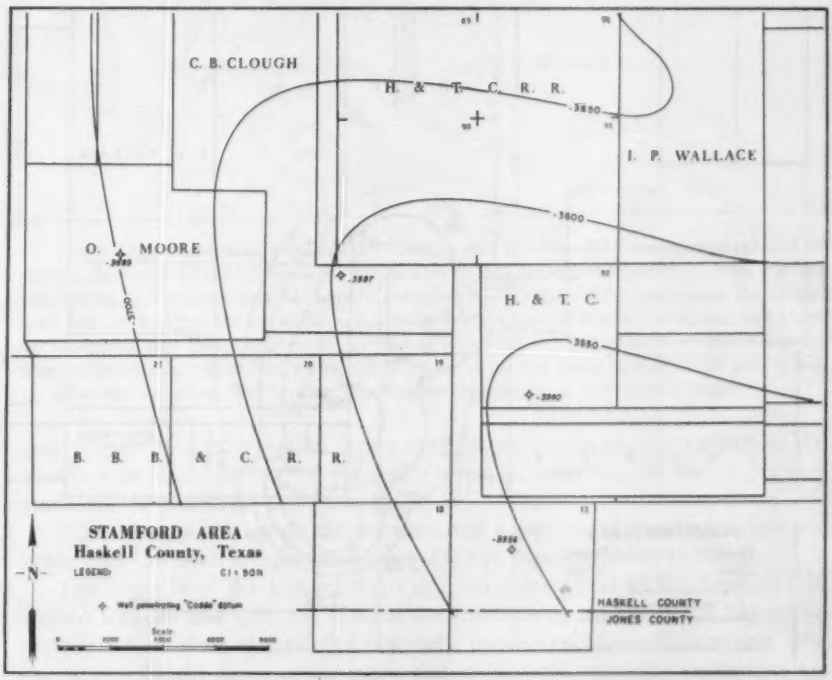

FIG. 3. Subsurface geologic structure of the "Caddo" limestone. The contours are also controlled in part by additional data outside the map area.

higher than the nearby wells on the seismic rim. This is summarized graphically on Figure 5.

The weight of the evidence from drilling to date is that the central depression apparent on the seismic map is in fact an illusion. Evidently seismic velocity in the central part of the reef is substantially less than in the outer part. In a sense, the reef has a "soft" core enclosed in a "hard" shell. This should not be surprising because the required lateral change in seismic velocity is no greater than the differences in measured interval velocity of different vertical zones in a single organic limestone reef in some wells in the region in which the seismic velocity of thick reef limestone has been measured. Figure 6 demonstrates the relationship between the thickness of reef limestone and the amount of apparent seismic relief on top of the "Caddo" limestone. (The term reef limestone as used herein includes all that closely related to, and practically inseparable from, organic reefs.)

The inference that there is no central depression is supported by the fairly continuous but irregular arch of reflecting horizons from the top of the reef upward, disclosed by seismic profiles like Figure 7, and by the shallower seismic

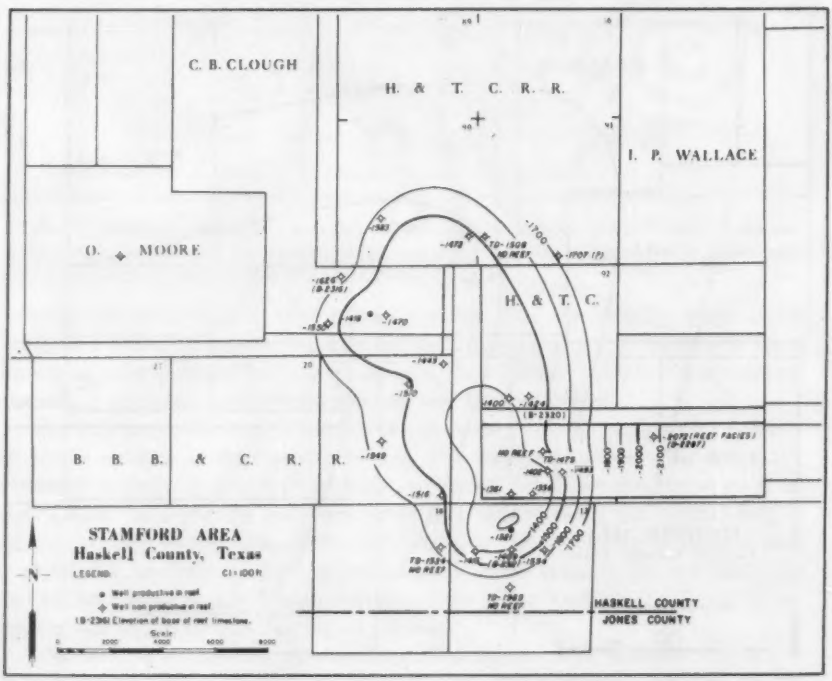

FIG. 4. Attitude of the top of the reef limestone as disclosed by drilling. Only wells to top of reef, or almost to it, are shown.

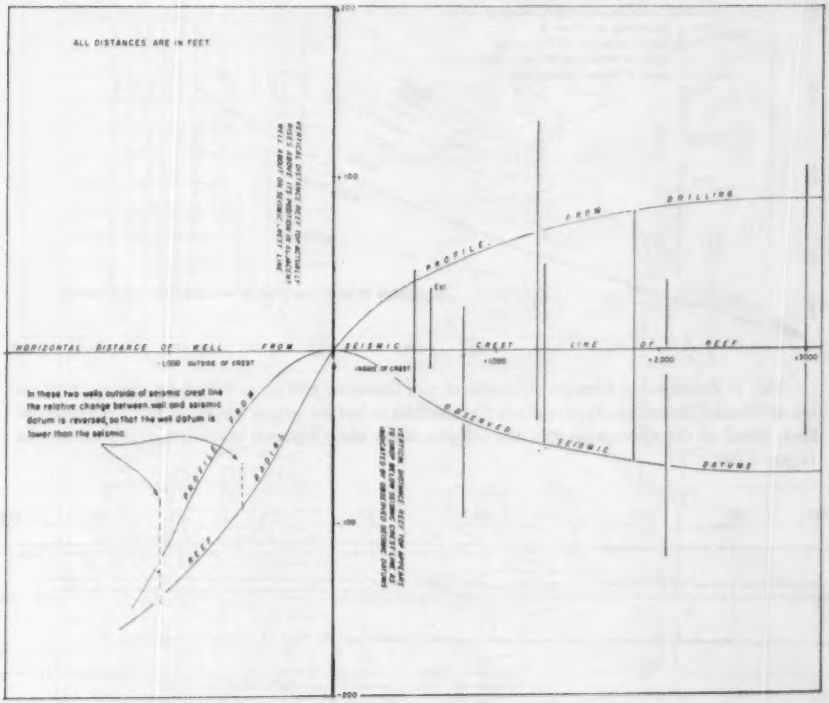
ALL DISTANCES ARE IN FEET
HORIZONTAL DISTANCE OF WELL FROM SEISMIC CREST LINE OF REEF
-1,000 OUTSIDE OF CREST
INSIDE OF CREST
+1,000
+2,000
+3,000
+100
-100
-200
In these two wells outside of seismic crest line the relative change between well and seismic datum is reversed, so that the well datum is lower than the seismic.
PROFILE FROM DRILLING
OBSERVED SEISMIC DATUMS
REEF

FIG. 5. Generalized radial profile of the Stamford reef as indicated by the seismograph and by drilling. Each vertical line represents one well, located off the seismic crest line of Figure 2 the distance indicated on the horizontal axis. The upper termination of each solid well line indicates on the vertical scale how much higher the top of the reef actually was encountered than in the nearest well about on the seismic crest line. The lower termination of each solid well line shows how much lower the observed seismic datums of Figure 2 indicated the top of the reef would be than at the nearby well on the seismic crest line. This demonstrates that the seismic central depression is illusory.

map, Figure 11. The reflection shown near −1,600 feet in the central part of the profile is at about the top of the reef. Generally, however, the top of the reef could not be picked on the seismograms.

Figure 8 shows the apparent correlation of some events on a typical seismogram with the electric logs of nearby wells, and Figure 9 shows lithology.

The attitude of the base of the Cisco limestone (base of Breckenridge) in wells is mapped as Figure 10. Most of the structure at this horizon is caused by compaction of shale around the relatively incompressible reef limestone. The sharp, bell-shaped dome at the south end of the reef, centering in Section 13, is a small residual high formed similarly by compaction of shale enclosing a local lens of Lower Avis ("Swastika") sandstone. The main features of Figure 10 show

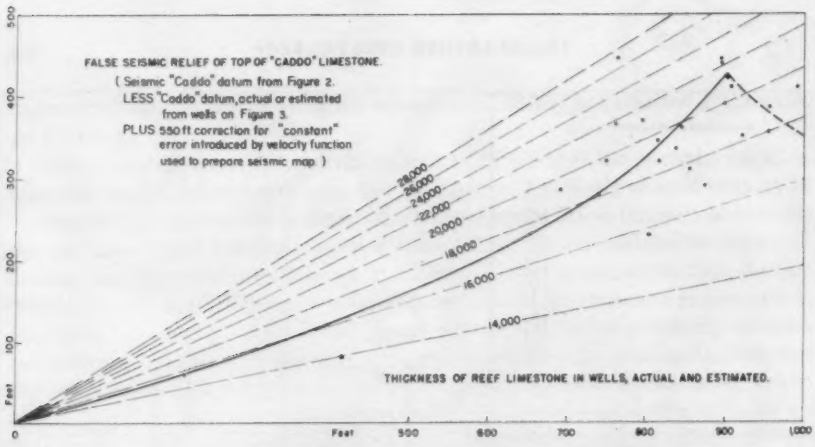

FIG. 6. Relationship between thickness of reef limestone and amount of false seismic relief on top of "Caddo" limestone. Apparent seismic velocities in feet per second are indicated by the diagonal lines, based on the assumption that the velocity of the shale replaced laterally by the limestone is 11,300 ft/sec.

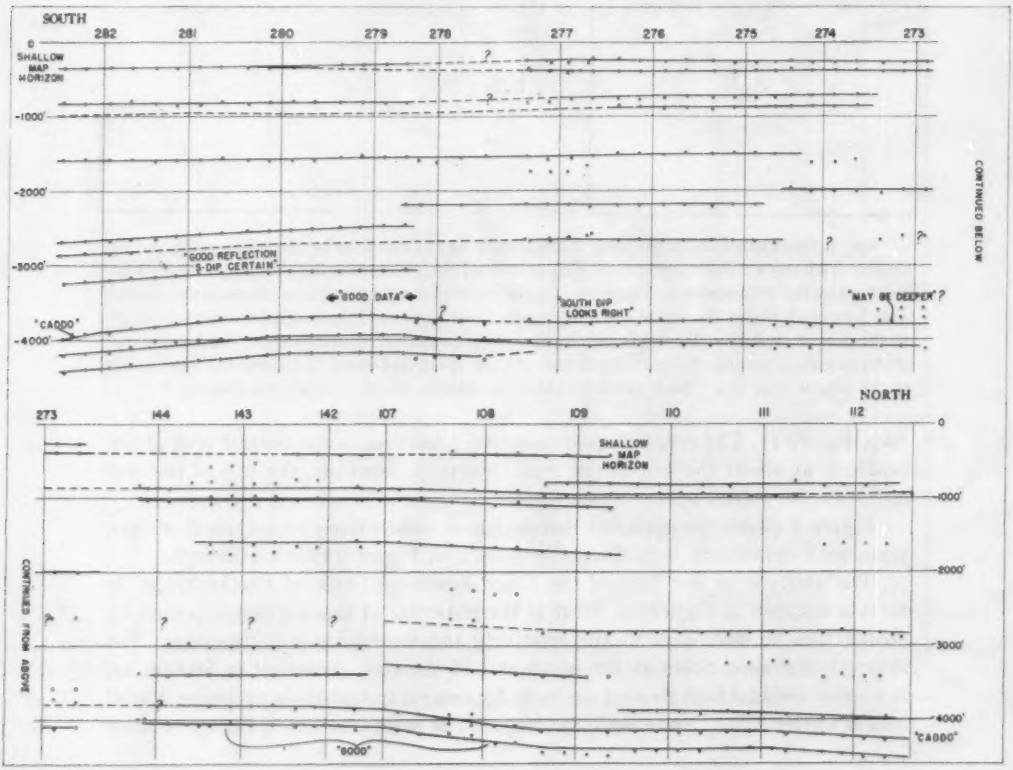

FIG. 7. Seismic profile across the Stamford reef. Depths indicated are about 10 percent greater than actually found by drilling. Figure 2 shows location of profile and shotpoints.

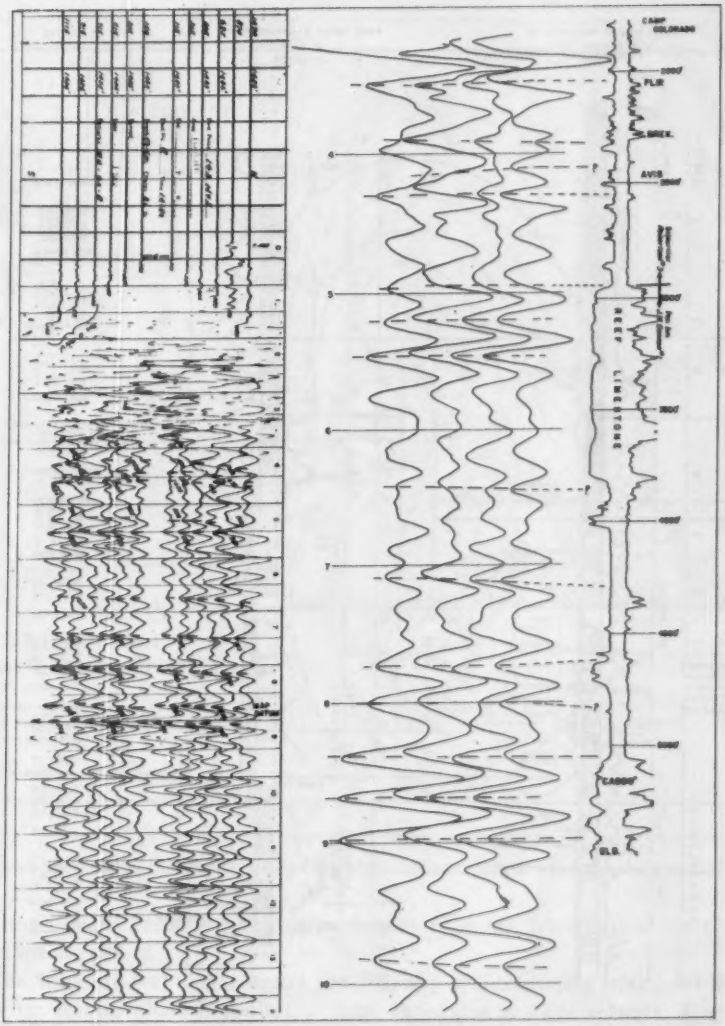

FIG. 8. Typical seismogram, shotpoint 143 on north flank of reef. Right, correlation of south half reflections with electric logs of nearby wells.

up on Figure 11, a shallow seismic map on about the Camp Colorado limestone horizon. Figure 12 is an electric log cross section through the Stamford reef which summarizes somewhat its stratigraphic and structural setting, and its effect upon "Caddo" reflections.

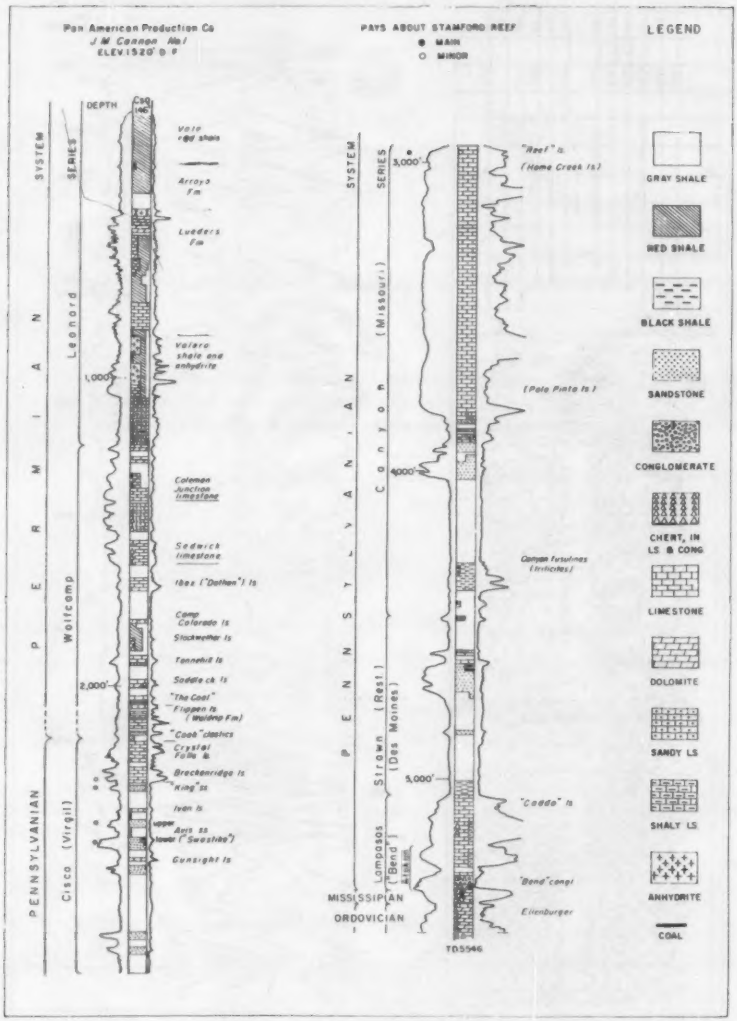

FIG. 9. Log of a typical well through the Stamford reef, showing lithology, spontaneous potential, and resistivity.

The Stamford reef could be mapped with the seismograph by means of the limestone's effect upon the travel time of reflections from the beds beneath because the limestone body is thick, at a shallow depth, and completely enclosed in shale, including both top and bottom. Velocity contrasts between limestone and shale are marked, sub-reef reflections persistent and distinctive, and com-

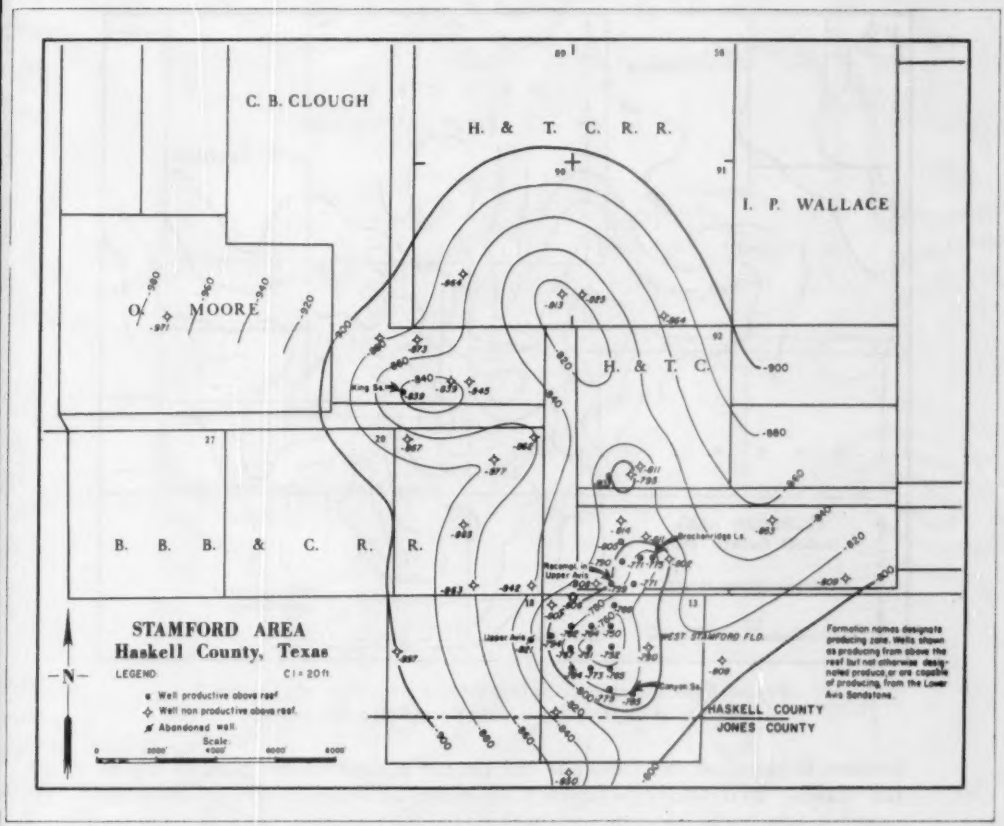

FIG. 10. Structure of the base of the Breckenridge limestone (base of Cisco limestone section).

plicating velocity changes which occur frequently in the lower part of the Cisco limestone are absent.

The Stamford reef demonstrates the difficulty of interpreting seismic work in limestone terrain which is subject to large variations in wave velocity. Even if velocity had been measured in every well drilled through the reef, the data still would not be sufficient to make a "mechanical" or "impersonal" seismic interpretation. The scale of lateral changes within such organic reef and similar limestones is likely to be so small that no practical grid of wells shot for velocity or logged acoustically could be close enough to disclose the pattern.

Velocity figures for the Stamford reef must be determined indirectly because no well in it has been shot or logged for velocity, and core properties have not been measured. It was estimated at each well location from the relationship

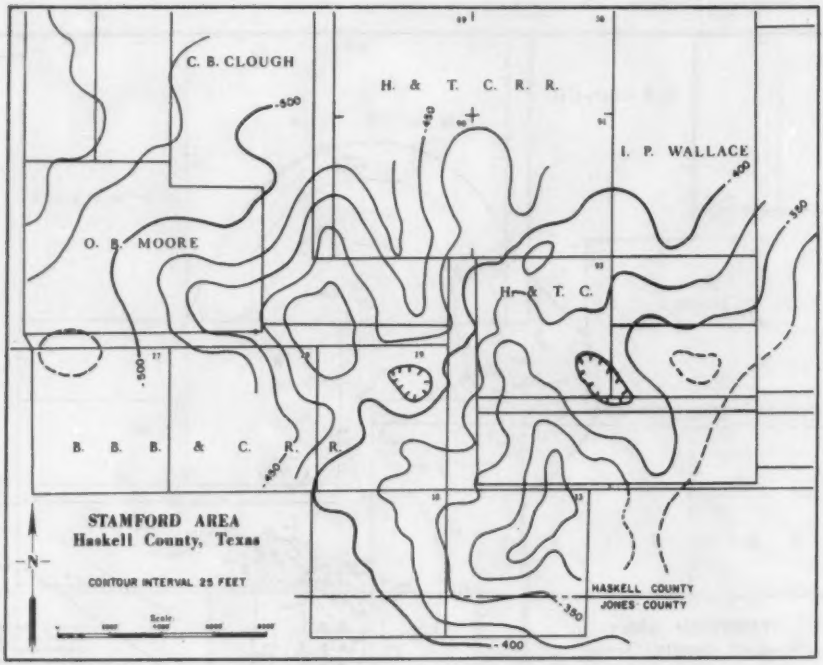

FIG. 11. Reflection seismograph map showing the attitude of a shallow horizon at about the position of the Camp Colorado limestone.

between thickness of reef limestone and amount of false seismic relief on top of the "Caddo," as indicated on Figure 6. To do this an assumption had to be made as to the velocity in the shale replaced laterally by limestone; a figure of 11,300 ft/sec was used, based on interval velocity measurements available on three suitable wells in the region. The velocity estimates, plus certain additional figures, were used with Brandt's (1955) equation 29 to estimate the porosity. Results are shown in the table below. Note that all these figures are averages through the entire thickness of reef limestone at the well locations.

Position on reef	Seismic velocity	Porosity
Seismic rim	19,500 ft/sec	5.7%
Seismic depression	17,500	7.2
Average for reef	19,000	6.0
Maximum observed	22,200*	8.9
Minimum observed	15,800	4.5

* Two higher values, shown on Figure 6, are attributed to a systematic inaccuracy in estimating the attitude of the reef base.

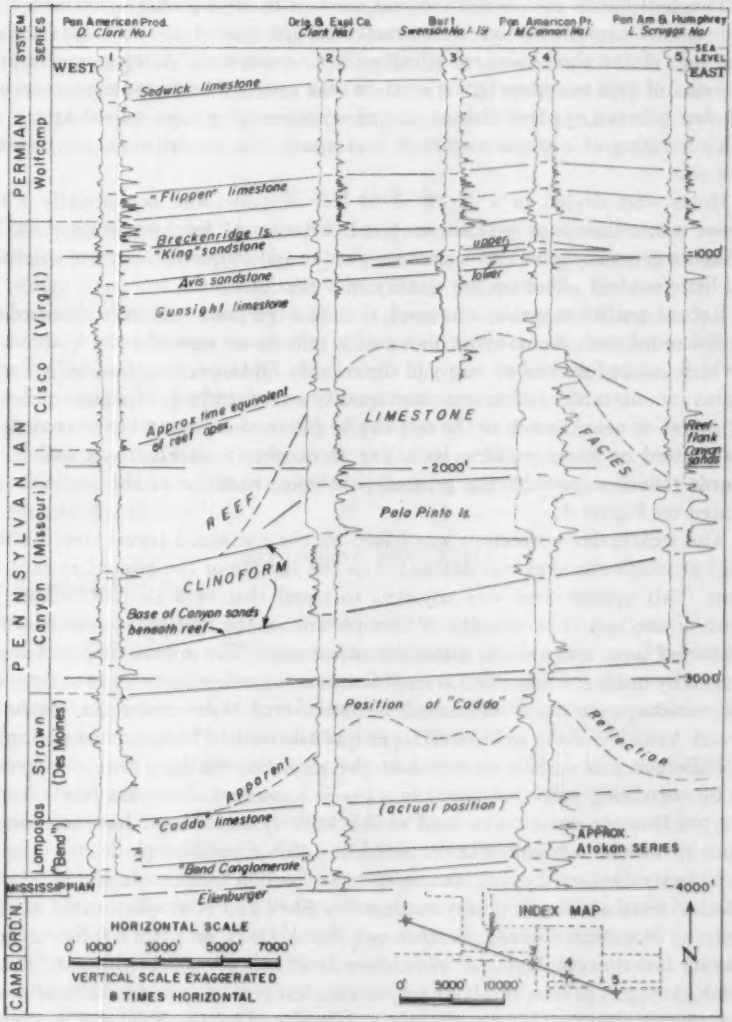

FIG. 12. Electric well-log cross-section through the Stamford reef.

SEISMIC PROCEDURE NEAR THE STAMFORD REEF

The continuous profile method was used, with shot points 1,300 feet apart. Each spread consisted of 12 seismometer groups spaced 200 feet apart, six on each side of the shot hole, recording on a 12-trace unit. A seismometer group consisted of two seismometers spaced 70 feet apart. Some supplementary work had shot points 1,035 feet distant, and 18 seismometer groups spaced at 115 feet, each consisting of 2 seismometers 50 feet apart. No special weathering spreads were shot.

Holes were drilled to a depth of 60 feet in shale, and occasionally a little deeper where limestone was encountered. Charges of from 10 to 30 pounds of dynamite generally gave the desired amplitude and frequency. Surface conditions had little evident effect on the quality of reflections.

Record quality generally was good, though a few poor ones were obtained over the Stamford reef. As many as nine usable reflections were observed, about half of which can be followed on many of the records. Of these, the "Caddo" reflection retains its outstanding character and quality over hundreds of square miles. An horizon at or near the top of the reef can be followed on a number of records and was plotted on some profiles, including those shown as Figures 7 and 8. The records reflect somewhat the general lithologic character of the section, as indicated on Figure 8.

The weathering correction was based on the measured travel time from the point at which the shot was detonated to the surface of the ground at each shot point. This uphole time was adjusted to equal that of a shot detonated at a depth of 100 feet. The velocity of that portion of the hole which was below the weathered layer was used to make the adjustment. The uphole time was supplemented by using the refraction arrival times on the reflection records to determine any variations in the thickness of the weathered layer under the instrument spread. Velocity of the weathered layer was assumed to be 2,000 feet per second.

Differences in surface elevation at the recording stations were compensated for by correcting reflection times to a plane 1,300 feet above sea level. A figure of 3,500 feet per second was used as the velocity of the zone between the 100-depth to which each hole was corrected and this 1,300-foot plane.

Velocity data used to convert corrected reflection times to depths in feet were obtained from a velocity survey made in the Shell #1 Patterson, located in northwestern* Stonewall County (Section 393, Block D, H. & T. C. RR Survey). The velocity function employed in the Stamford reef area gives depths to the "Caddo" which average 550 feet, or about 10 percent, too great at nearby wells where reef limestone is absent. This discrepancy is introduced by the Shell well having 650 feet of reef limestone with velocity 50 percent higher than average, more limestone in the overlying section, and by correlative stratigraphic horizons occurring at greater depths.

A number of data were computed from the averaged corrected reflection

* Stonewall County adjoins Haskell County on the west.

times for each reflection used on each record. These points were plotted on cross sections constructed along each traverse, and the correlation of individual reflecting horizons shown by connecting lines, as on Figure 7. The datums used to make the contour maps are the average of the plotted datums beneath each shot point. In comparing the seismic datums with those in wells, one must keep in mind that the seismic depths run 10 percent greater than well depths, and that superimposed on this background are the effects of the lateral variations in wave velocity.

GEOLOGIC BACKGROUND

The terrain over the Stamford reef is gently rolling, with elevations ranging generally from 1,500 to 1,550 feet above sea level. The surface formation is Vale red shale, near the middle of the Clear Fork group in the Leonard series of Permian age. The sedimentary section is about 6,000 feet thick, consisting predominantly of shale and limestone, with subordinate sandstone and anhydrite. Figure 9 illustrates its general character. The pre-Cambrian basement is presumed to consist of granitic and meta-sedimentary rocks.

Structurally, the reef lies on the west flank of the Bend Arch, 60 miles from its axis. Around Stamford regional dip is about west-northwest 40 feet per mile ($\frac{1}{2}°$). Figure 3 shows a gentle anticline plunging toward the northwest beneath the Stamford reef.

THE ORGANIC REEF BELTS

The Stamford Reef Belt

The extensive seismic survey that found the Stamford reef disclosed also material of similar nature but thinner in a seemingly continuous, well-defined belt 2 to 4 miles wide which extends northeast from the Stamford reef for 25 miles, to the edge of the surveyed area. Reefs are not nearly as well developed elsewhere along it, except at the Humphrey-Chapman Oil Field in central eastern Haskell County. The belt gradually changes its trend from northeast near the Stamford reef to almost due north through the Humphrey-Chapman Field. South and southwest of the Stamford reef the "Caddo" reflection becomes so "low" that the belt of marked reef development could not continue any farther to the southwest. Subsurface mapping shows that the general belt of well developed reefs turns to an easterly direction at its culmination near Stamford. It extends east through Strand Field on the Haskell-Jones county line, then shifts to southeasterly through North Avoca Field and finally south and southwest through Avoca and Griffin Fields in northeastern Jones County. The map of Robert Wesselhoeft, Jr. (1949) on the top of the Canyon reef shows relations in these fields.

The amount of seismic relief along the Stamford reef belt varies tremendously, indicating corresponding variations in either seismic velocity or thickness of the reef limestone. Well logs demonstrate that the relief is due principally to local changes in limestone thickness, and that practically all the change is in the elevation of the top. The bases of all the reefs in this belt seem to lie at an almost

identical stratigraphic horizon. From this it is inferred that seismic relief in the strike direction is a function primarily of reef limestone thickness which is controlled by the level to which reef growth persisted at each locality. That is why the high "Home Creek" reef at Stamford can belong to the same reef belt as thinner, lower "Palo Pinto" reefs.

The Stamford reef rests on sandstone and shale deposited in a topographic form which in profile resembles the classic delta, with top-set, fore-set and bottom-set beds. To avoid confusion, a set of terms proposed by John L. Rich (1951) is used for these features. The terms *unda* ("wave"), *clino* ("slope") and *fondo* ("deep") designate respectively the environment or facies of these three elements of deltaic topography; and the suffix *-form* is appended to designate the topographic unit represented by each. Thus the *undaform* is the topographic unit expressed by top-set beds, and the *clinoform* corresponds to fore-set beds.

The Stamford reef began its growth near the seaward edge of an undaform, as indicated by the profile of its base on Figure 12 and by mapping along this belt with electric well logs. The sandstone body directly under the reef was laid down near the outer edge of the undaform and on the clinoform as demonstrated by its feathering out and the descent of its base and top westward, also shown on Figure 12. This undaform-edge sand body was deposited in shallow water, so marked subsidence must have followed to allow 1,000 feet of reef limestone to accumulate on top of it. During this subsidence the Stamford segment of the reef belt continued to grow much longer than the rest, perhaps because of the gentle anticline beneath it, shown on Figure 3, and its exposed position along the belt where more nutrients may have been available.

Additional Reef Belts

Two more reef belts of slightly different type but with similar seismic expression were mapped the same way. These show up on the seismic map also as "structurally high" belts with numerous small, fairly sharp, contour closures which give the map a much finer "grain" or "texture" than it possesses elsewhere. They are referred to as *undaform-edge reefs* (or banks) for reasons that are evident on Figures 14 and 15.

One undaform-edge reef was mapped on the "Caddo" reflection for 10 miles across central eastern Haskell County and into Shackelford County. Figure 13 is part of this map. The reef shows up as a sharp, continuous seismic ridge 1.2 to 2 miles wide and from 100 to 200 feet (or more) high, with numerous small closures on top. A number of wells drilled on and straddling the seismic ridge about 4 miles east of the Humphrey-Chapman Field disclose that it coincides with the Ranger (?) limestone undaform-edge, as illustrated on Figure 14. Variations in thickness of this limestone are not nearly enough to account for all the seismic relief mapped, so there must be also lateral changes in seismic velocity of the limestone. Since the feature makes a pronounced seismic ridge, these velocity changes must occur along belts parallel to the trend of the reef, corresponding to

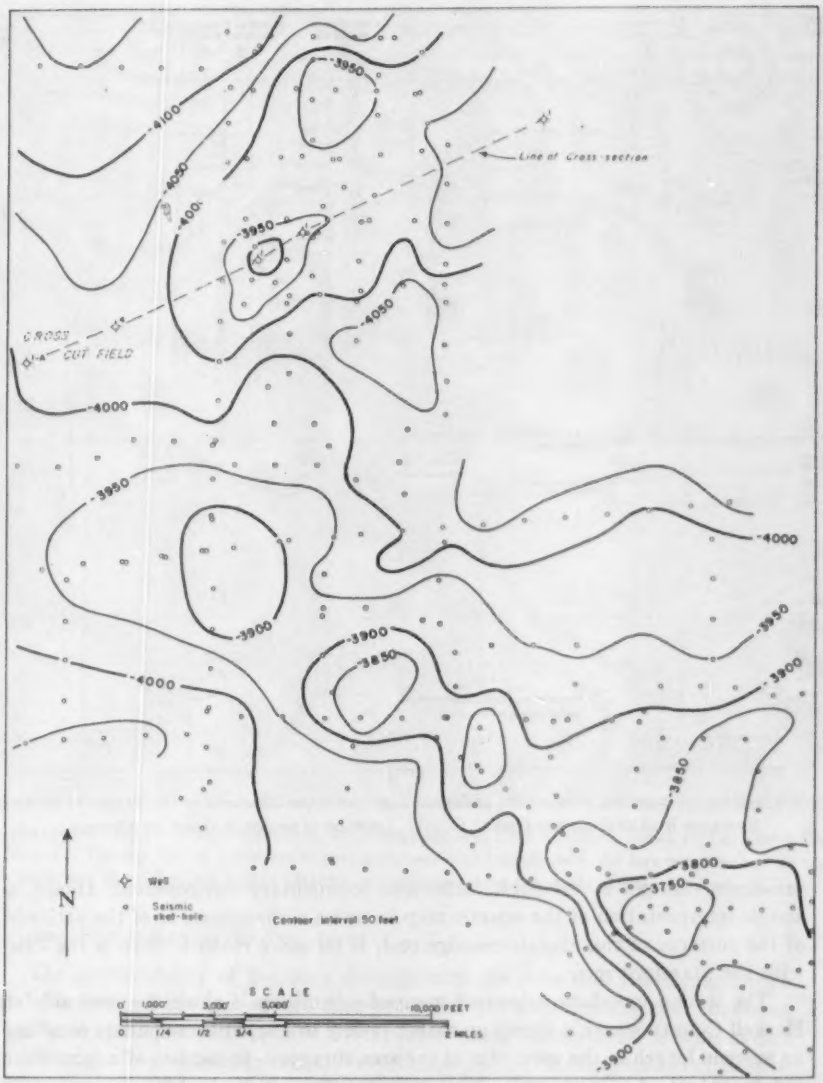

FIG. 13. Reflection seismograph map showing false structure of the "Caddo" produced by an undaform-edge reef in central eastern Haskell County. The only wells shown are those on the cross-section, Figure 14. Additional dry holes condemn the seismic ridge, while the one oil field on the map is located in a seismic syncline.

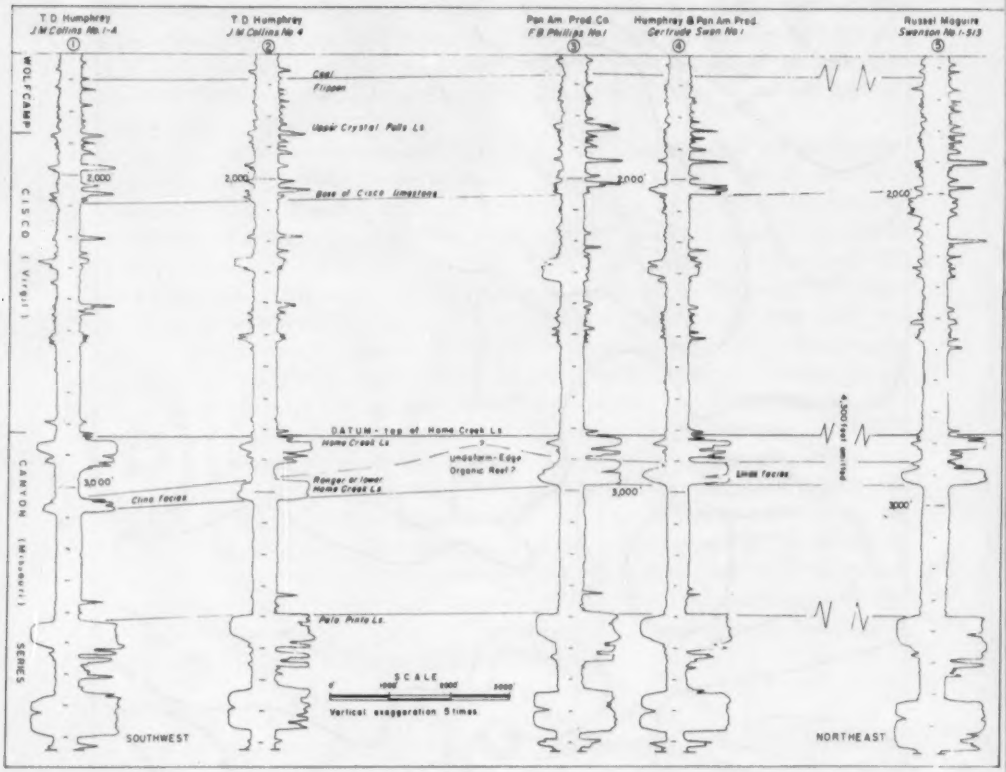

FIG. 14. Electric well-log cross-section showing the undaform-edge and upper clinoform of the Ranger or lower Home Creek limestone in central eastern Haskell County. Location of section is shown on Figure 13.

presumed changes in lithologic facies and sedimentary environment. Hence, a simple interpretation of the seismic map in terms of structure, or of the attitude of the surfaces of this undaform-edge reef, is no more realistic than is the case with the Stamford reef.

The second undaform-edge reef mapped seismically is along the west side of Haskell County where it shows up rather poorly in 2 separate segments totalling 10 miles in length at the very edge of the area surveyed. It consists of a somewhat indefinite belt 2 to 4 miles wide which appears "structurally high," with numerous small "closures." This seismic anomaly belt follows the zone in which several basal Cisco limestone units thicken markedly and pass off the edge of the undaform onto the clinoform. Figure 15 illustrates this feature where it can be cross-sectioned readily along strike in and near the Kiowa Peak Field of northeastern Stonewall County.

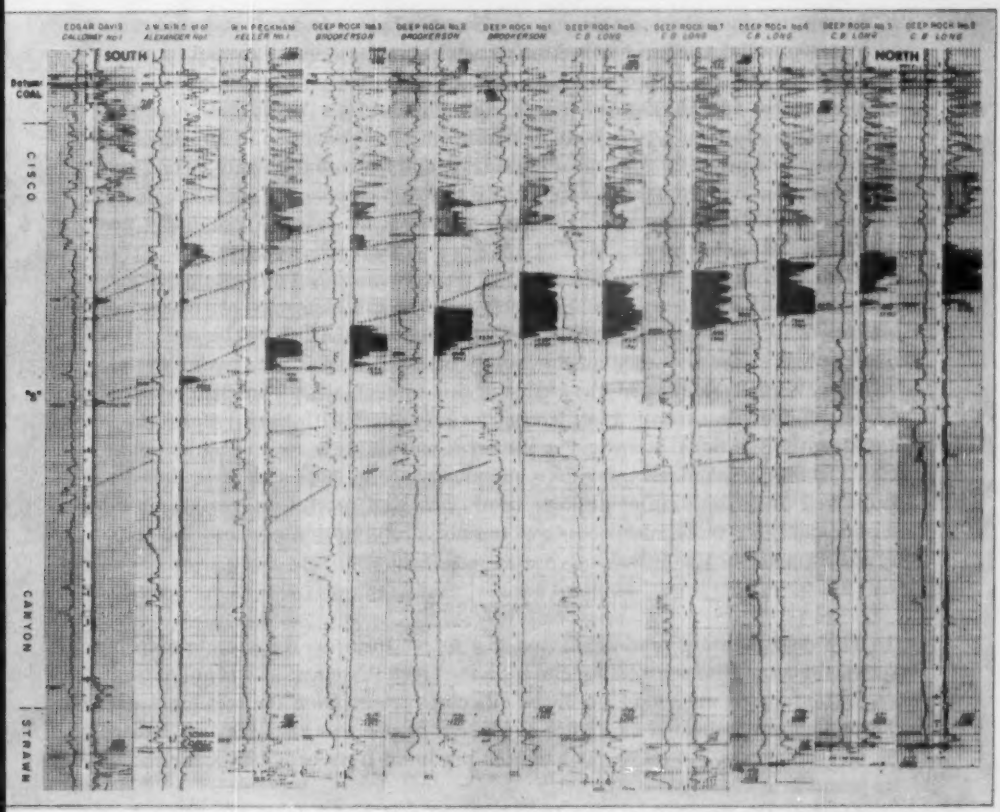

FIG. 15. Electric well-log cross-section showing undaform-edge and clino limestone bodies in the Kiowa Peak Field ortheastern Stonewall County, Texas. These are in part undaform-edge organic reefs. All logs but the three on the left are f direct offset wells, and these three are logs of nearby tests projected along the strike of limestone body "S."

Seismic Exploration in the Reef Areas

The practicability of mapping directly with the reflection seismograph such undaform-edge reefs and related limestones has not been investigated. However, Pan American geophysicists have not reported seeing "anomalous" seismic events which might be due to such cause. Nevertheless, a careful examination of seismograms along suitably located profiles might well disclose evidence of sloping clino limestone bodies, just as scrutiny of electric log cross-sections has revealed the phenomenon where it had not been noticed before. John Daly (1956) has reported observing steep "reef dips" reflected from a much more highly developed feature of this type where it crosses Hockley County, 150 miles west and slightly north of Haskell.

In this province considerable seismic effort has been expended, and numerous exploratory wells have been drilled, on non-existent "anticlines" caused by these rapid lateral changes in the thickness and seismic velocity of limestones related to organic reef and bank development. Some of the tests have been successful fortuitously, both because a body of porous limestone enclosed in impermeable shale may be a perfectly good oil and gas trap, and because relatively incompressible limestone flanked by shale frequently makes a compaction anticline in the superjacent beds. Other wells have been successful for reasons completely unrelated to the seismic work.

Seismologists and geologists generally have been much too prone to pat themselves on the back, or to denounce their luck, as the case may be, instead of learning why their "shooting structure" sometimes faded before the drill. It is time to look more seriously at the causes of rapid lateral changes in seismic velocity. Without additional knowledge of this subject, seismic interpretation of the less obvious features in many areas (not only those with thick limestones) is not an entirely rational science. The answer is not simply more and better equipment, techniques, and data, for those may lead only to more and better falacies. Improved understanding of geologic conditions, and careful integration of the seismic data, are essential for effective seismic interpretation of subsurface geology in an area such as this.

OIL OCCURRENCE

The disappointing production and distinctive form on the seismic map inspired the name "none atoll" for the Stamford reef. "None at all" is not entirely accurate, for two wells have produced oil commercially from the reef limestone. These wells are indicated on Figure 4, where it can be seen that they are located on reef eminences. No oil or gas has been produced from beds below the reef in its immediate vicinity.

Most of the production over the Stamford reef comes from the lower Avis sandstone and conglomerate in the West Stamford Oil Field, as indicated on Figure 10. The sand body pinches out regionally eastward, and where it passes above the reef it is elevated and pinched-out laterally. Thus the trap is primarily stratigraphic, but it is localized "structurally" by differential compaction above the reef limestone.

The upper Avis sand, which merges into the lower Avis in the more down-dip wells as shown on Figure 12, has produced in two wells and is capable of production in some additional lower Avis producers. The Pan American No. 1 Watson produced for a time in the upper Avis, and the former Pan American No. 1 Kieke-Scott Unit 3 was recompleted in it.

Three additional zones have produced in one well each. Canyon sand entering the section off the south flank of the reef produces oil in the Burt No. 11 Swenson. Ten feet of sand separated by 15 feet of shale from the rest of the "King" sand section is productive in the former Pan American No. 1 W. E. Clark above the

west flank of the reef. This is probably a very small stratigraphic trap (seen on Figure 12), possibly with lateral closure afforded by the compaction anticline over the reef. The Breckenridge limestone produces in the Pan American No. 1 Kiecke above the east flank of the reef near its south end.

CONCLUSIONS

1. The Stamford reef, and other reefs in this area that have a substantial thickness of shale and sandstone beneath, can be mapped with the reflection seismograph because of their velocity effect. This particular stratigraphic setting provides an opportunity for seismic waves to be reflected from beds below the reef and to pass through the limestone, where they are accelerated to produce a false structure proportional to limestone thickness and seismic velocity contrast.

2. Detailed interpretation of the seismic map over such a reef or reef belt in terms of the configuration of the reef, or in terms of the structure of underlying strata obscured by the reef, is not possible with present knowledge. Lateral changes in seismic velocity seem to be too rapid for any practicable grid of wells shot or logged for velocity to be close enough for an "impersonal" interpretation. The best approach seems to be improved geologic understanding of the reefs and of the subtle changes in lithology that modify seismic wave velocities.

3. Much seismic effort has been wasted, and many futile exploratory wells drilled, on non-existent "anticlines" caused by rapid lateral changes in the thickness and seismic velocity of organic reef limestones.

4. The Stamford reef is a remarkable example of the difference between seismic closure, an obvious trap by subsurface geology, and the location of a good little oil field.

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GEOPHYSICS, VOL. XXII, NO. 3 (JULY, 1957), PP. 630–642, 6 FIGS.

GRAVITY SURVEY OVER A GULF COAST CONTINENTAL SHELF MOUND*

L. L. NETTLETON†

ABSTRACT

A gravity survey of 50 stations over one of the mounds near the edge of the Continental Shelf developed a strong, roughly circular negative anomaly. The gravity minimum is similar in magnitude and lateral extent to those over large salt domes in the on-shore and explored offshore areas of the Gulf Coast. An approximate quantitative evaluation shows that the minimum can be accounted for quite completely by a large shallow salt dome. The shallow part of the dome is approximately coextensive with the topographic feature and it seems quite certain that this particular mound is genetically related to a salt dome. If other similar mounds also are salt domes, the area of domes off the Louisiana coast is approximately doubled over that presently known from commercial geophysical exploration.

INTRODUCTION

This paper gives the results of a gravity survey over a topographic "mound" about 125 miles southeast of Galveston and near the outer edge of the Continental Shelf. In view of the very considerable interest in the Continental Shelf mounds and the high degree of speculation in the various suggestions as to their origin which have been made by several writers on these features, a definitive geophysical survey was obviously desirable.

The mound chosen for the program is near the reference point "WAY" on U.S.C. & G.S. chart No. 6292, and is referred to here by that name. Its minimum depth is at latitude 27°52′, longitude 93°49′ (see index map, Fig. 1). This same mound is the westerly of two shown by Carsey (1950 Fig. 12‡, p. 37), and his map is repeated by Goedicke (1955) as Figure 2. The same area is also shown, in greater detail, by Parker *et al.* (1956) as Figure 2, where it is named "West Flower Garden Bank."

The existence of a large number of submarine topographic mounds off the Gulf Coast of Texas and Louisiana has been known for many years. The first mention of a mound apparently was made by Trowbridge (1930, p. 890) where he refers to coarse sedimentation on a "submarine dome that stands more than 100 ft above its surroundings" and, in discussion (p. 901) states that it "is one of many similar and similarly located elevations of the Gulf Coast of Texas and Louisiana." He suggested a diastropic or even volcanic rather than gradational cause.

Shepherd (1937) published maps of several mounds based on echo-soundings.

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‡ There appears to be an error on this map: The longitude line near its east edge should be 93°30′ rather than 94°30′ as shown.

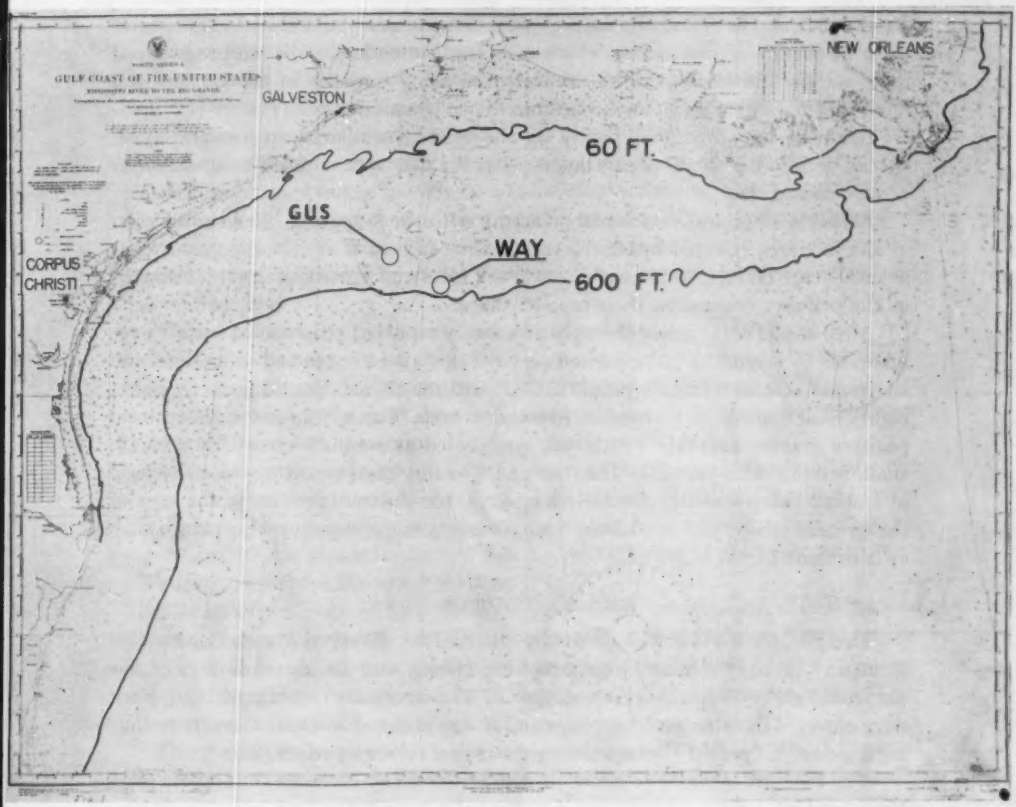

FIG. 1. Index Map showing two mounds where geophysical surveys have been made.

One of these, near the Mississippi delta, is a nearly circular mound, some five miles across, with some 300 ft of relief. Shepherd suggested that some of the mounds may be caused by salt domes.

Quite detailed topographic data over large areas of the floor of the Gulf of Mexico were made between 1934 and 1940 by the U. S. Coast and Geodetic Survey using fathometer records positioned by radio-acoustic ranging. The maps are unpublished but prints can be obtained from the Survey office in Washington. An extensive study was made by Gealy (1955), based on maps assembled from these data. She suggested that some of the mounds might be related to salt domes but considered this as probably a relatively minor factor.

Carsey (1950) considered these "smaller features of the Gulf Shelf" and indicated a count of 164 topographic features along the shelf off the coast of Texas

and Louisiana. He included a map of their distribution and a statistical study of their frequency of occurrence which indicated numerically the well recognized tendency for the mounds to be concentrated along the edge of the Continental Shelf and roughly along the 100 fathom depth contour.

Goedicke (1955) argued, partly on the basis of similarity in topography to that of certain Persian Gulf salt domes, that the Continental Shelf mounds might be salt domes also.

Parker *et al.* (1956), concerned primarily with the topographic form and fauna of the mounds, referred briefly to the possible influence of salt domes but considered other factors, such as changes in sea level and growth of organic deposits as the primary control on their present shape.

Allen *et al.* (1956) made the only previously reported geophysical survey over an off-shore mound. A quite limited survey (18 stations) over and around a small sharp pinnacle, at reference point "GUS," latitude 28°10′, longitude 94°18′ about eighty miles south of Galveston (see index map, Fig. 1) showed a sharp local positive gravity anomaly which was interpreted as possibly caused by a small, shallow dome with caprock. The "mound," in this case, consists almost entirely of a small sharp feature, generally similar to the central pinnacle in the area of the present study, but is without a surrounding larger topographic feature such as is present at "WAY."

THE GRAVITY OPERATION

The gravity survey was originally planned by Gravity Meter Exploration Company in 1955. Station locations were chosen and their coordinates in the electronic survey system were calculated. The necessary boats and equipment were engaged in commercial surveys and it was planned to make the survey during a 4-day "off period" between the regular 10-day work periods.

The first opportunity to attempt a gravity survey arose in December, 1955. Unfortunately, the weather turned bad on the second day and less than half of the planned stations were observed. Another attempt was made in July, 1956 when the entire program, as originally planned, was carried out with a total of 50 observations which included repetition of the stations of the first attempt.

The general gravity operation was carried out with the same equipment and methods used for commercial underwater gravity surveys. The boat used, the motor vessel GMX II, is a converted 104 ft, twin-screw sub-chaser. Observations were made with a La Coste-Romberg remotely controlled underwater gravity meter. Water depths were measured by a pressure tube with its open end at the meter and connected to an air reservoir on the boat. Excess air pressure in the reservoir bleeds off through the tube until it is balanced by the hydrostatic pressure of the water at the meter and this pressure is read by carefully calibrated gauges. Locations were provided by the Raydist phase comparison system up to distances of 150 miles from the fixed shore stations. The gravity observations were made without anchoring the boat which is held close to a small anchored marker by manipulation of engine throttles, clutches and rudder. The only modi-

fication of usual commercial operating procedure was the use of greater lengths of hoisting and electrical cable on the meter to permit operation at greater than normal depth. The maximum depth of observation was 465 ft.

One special condition was observed. From the first attempt it was realized that any observation on the shallowest part of the mound would be hazardous because of very ragged coral. Therefore, the observation program was laid out to make any readings on the shallow pinnacle after all other stations were completed. This turned out to have been a valuable precaution. After completing the first attempted meter reading on the pinnacle, great difficulty was encountered in recovering the meter, some of the electric cable was badly cut and one leg was torn loose on the meter. The survey was necessarily terminated forthwith but the last reading was valid.

Figure 2 shows the gravity stations, observed gravity values on an arbitrary datum and contours a 1.0 mg interval. The stations are mostly at about 5,000 ft. spacing along four diameters across the central part of the mound. The lines are short to the south because of the rapid increase in water depth as the meter case is designed for a safe maximum depth of about 500 ft.

The stations are reduced in the usual way, with elevation correction of 0.071 mg/ft corresponding to a density of 1.80, latitude correction and a correction for the upward attraction of the water over the meter. A terrain correction of .30 mg was added to the pinnacle station, No. 49, elevation −72 ft. Such corrections were insignificant for the other stations.

The observed gravity map shows a very large, roughly circular minimum which dominates the entire area of the survey. It is obvious, now that the work is done, that some stations should have been made farther out to give wide control for the regional background, but the large size of the minimum was not anticipated when the work was planned.

The gravity relief is considerably greater on the west and northwest flanks of the minimum than it is on the east flank. This asymmetry indicates a generally northeasterly regional gradient of about 0.4 mg/mile, as shown by the dashed, straight line contours on the residual gravity map, Figure 3. Subtraction of this regional leaves the residual values and contours as shown on the residual map. The residual minimum is fairly circular and symmetrical except for the prominent embayment to the north. The indicated negative relief is nearly ten milligals which is large, but not unreasonable, for a salt dome gravity anomaly. For instance, the gravity minima at the Humble, South Liberty and Lake Washington domes each have approximately 10 milligals relief.

ANALYSIS OF THE GRAVITY ANOMALY

Considering its geological environment and general similarity to minima at known salt domes, we have assumed that the present anomaly is caused by a salt dome and have made an approximate determination of the form which the salt may have. The result is shown by Figure 4.

The "Residual" curve on this figure is taken from the residual gravity values

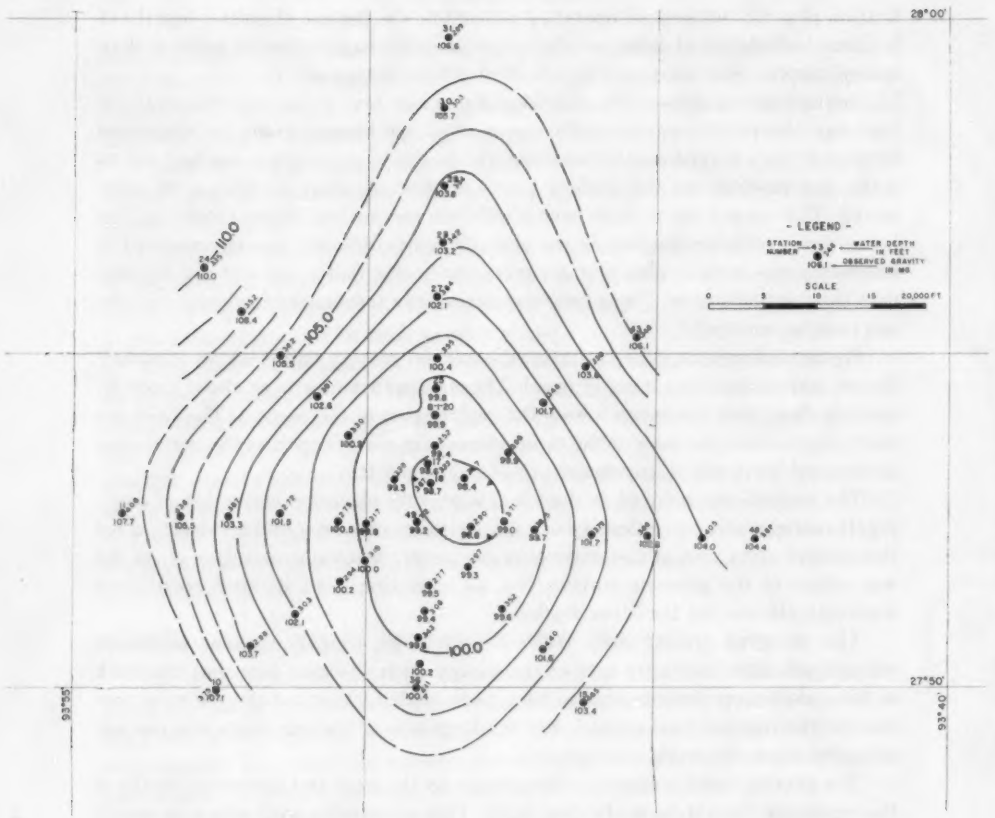

FIG. 2. Observed Gravity Map; contour interval 1.0 mg.

on the east-west line of stations of Figure 3. The "Calculated" curve shows the gravity effect of a circular dome with the cross section shown. The gravity effect was calculated from the several circular discs shown in the section with the negative density contrast increasing with depth in a manner similar to that indicated by an earlier curve for the relation of density with depth (see Nettleton, 1934, p. 1179). Later experience has indicated that this curve should be lower in upper and intermediate depth ranges and that the "cross over," at which sediments and salt have the same density, is at greater depth than the approximately 2,000 ft point indicated on that curve. This is particularly true for domes in areas of very thick deposits of recent sediments, such as near the Mississippi Delta and probably off-shore also, where there has been less geologic time for compaction and lithification of the shales. For the present calculation, the "cross-over" depth is

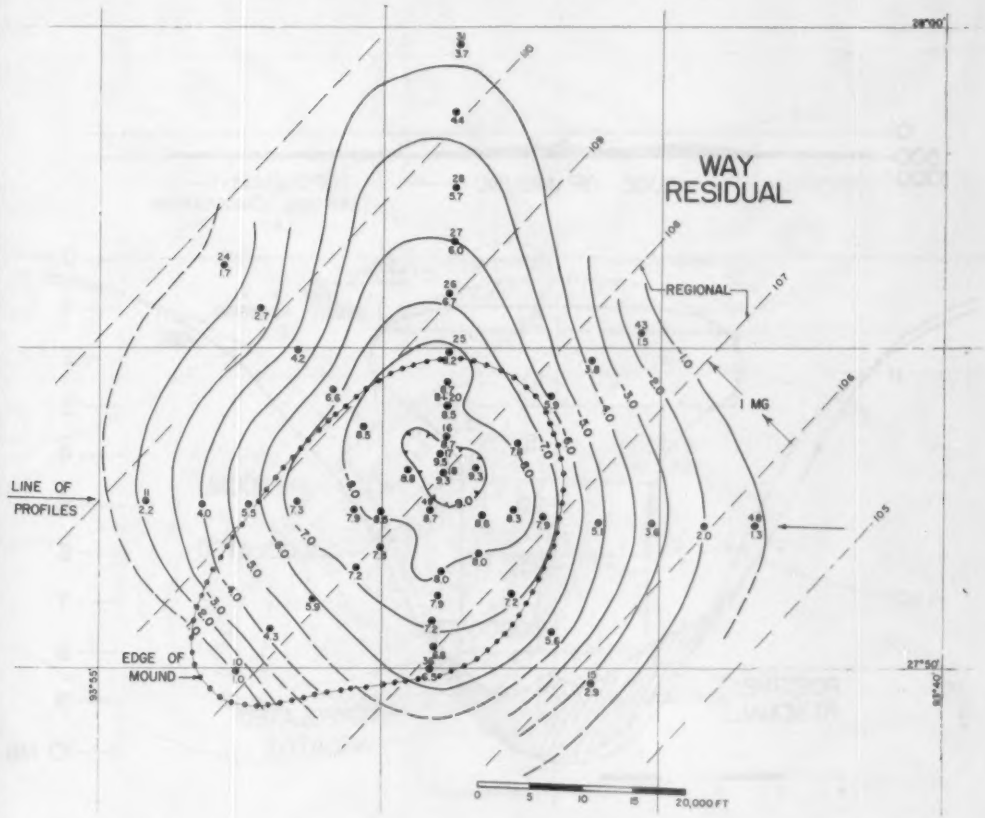

FIG. 3. Residual gravity contours after subtraction of regional shown by dashed straight lines; contour interval 1.0 mg.

taken at about 4,000 ft as indicated by the "zone of density reversal" of Figure 4.

The gravity calculations were made by means of a chart for solid angles for circles (Nettleton, 1944).

The overhanging dome form shown in the section was assumed to give a calculated curve with a relatively flat bottom and steep flanks and with the estimated total gravity relief of the residual gravity profile. This form is entirely reasonable but cannot be considered as unambiguously established, primarily because of uncertainty in the regional and the resulting uncertainty in estimating the depth of the minimum. This, of course, results from the fact that the survey does not extend far enough beyond the anomaly to determine the regional very reliably. Also, the form of the calculated dome is influenced by the assumed 35,000 ft depth to the base of the salt column.

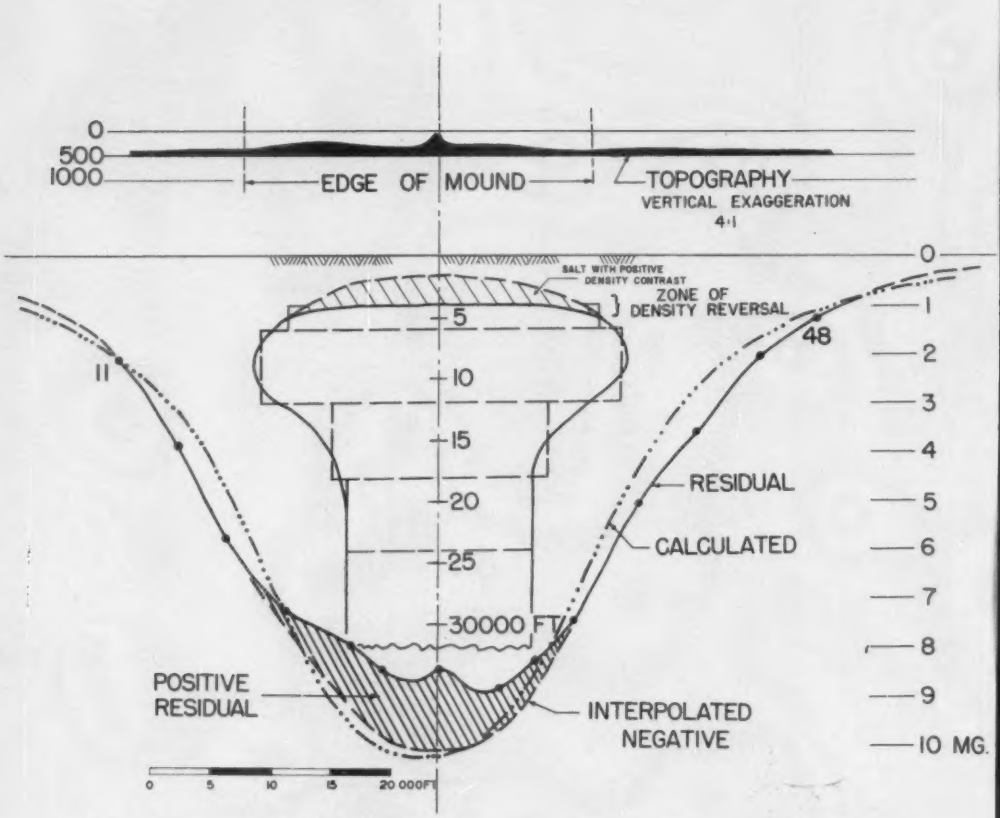

FIG. 4. Residual and calculated gravity profiles, elevation profile and dome cross section along east-west line shown in Figure 3.

Because of the limits of the control, no attempt has been made to account for the northward embayment. It is possible that this is caused by another dome beyond the northern limits of the control. The hydrographic map gives no definite suggestion of a topographic feature which can be related to this suggestion.

The central part of the residual gravity minimum is somewhat irregular and is not accounted for by the calculated effect. If we draw the "Interpolated Negative" effect as shown on Figure 4, making the curve correspond approximately with the calculated effect, it is about 1.8 mg below the "Residual" curve at the center of the anomaly. The difference between the two curves is the "Positive Residual" effect indicated by the shaded area on Figure 4. This is not accounted for in the calculation of the salt effect. This "Positive Residual" is attributed to

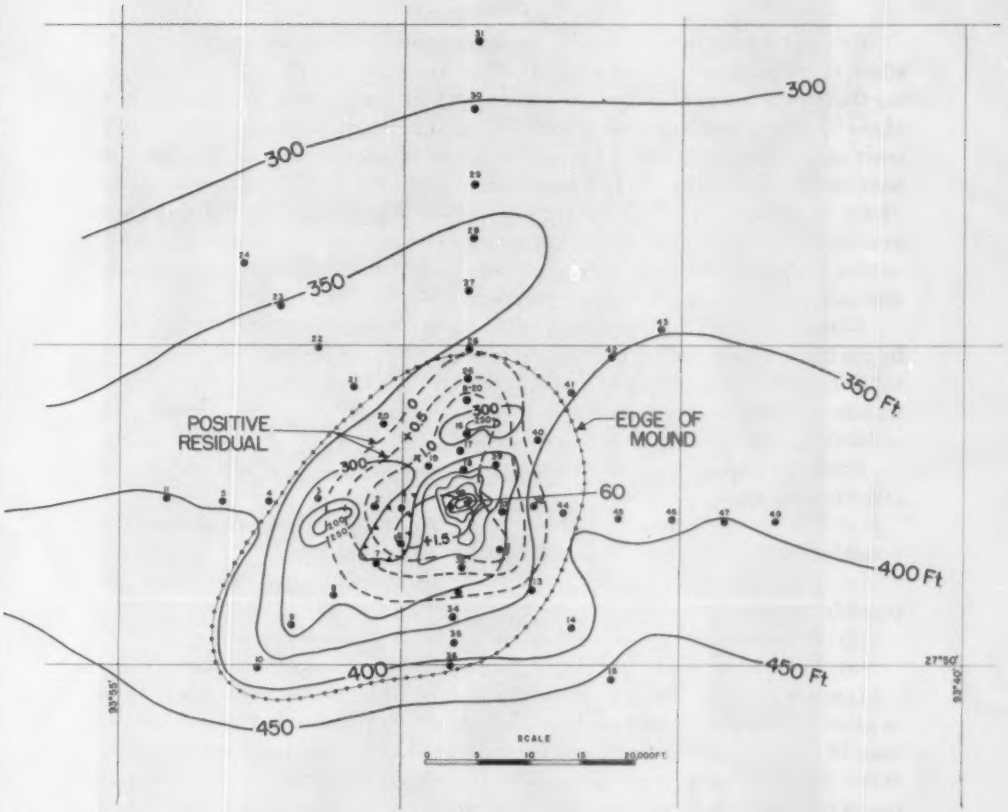

FIG. 5. Topographic contours from water depths at gravity stations, supplemented by bathymetric map by Parker, *et al.* (1956); contour interval 50 ft. "Positive Residual" contours (dashed lines) correspond to shaded area on residual gravity profile as shown in Figure 4.

shallow positive density contrasts. It could have its origin in (1) shallow salt above the zone of density reversal, (2) caprock, (3) uplifted sediments over the dome, (4) local coral growth over a dome, or (5) combinations of these effects. With the relatively widely spaced control and lack of any physical contact on the probable dome we can only speculate on which of these possible effects predominates. Because the dome apparently has affected the surface topography, it is probable that the dome is very shallow. Therefore, our best guess is that the shallow positive effect is primarily from shallow salt. This is indicated in Figure 4 by the dashed upper part of the dome, above the zone of density reversal, as shown in the cross section.

RELATION TO TOPOGRAPHY

We have made a contour map of the shallow positive component of the gravity effect, corresponding to the shaded "Positive Residual" of Figure 4, by subtracting the residual value at each station, as shown by Figure 3, from smooth contours of the "Interpolated Negative" effect (Fig. 4). The result is shown by the dashed positive contours, from 0 to +1.5 mg, in the central part of Figure 5. The general background contours, at 50 ft interval, are generalized bottom topography. The "Edge of Mound" as shown by the line of dots is intended to indicate the approximate outline of the area of the topographic feature as a whole. The same outline is shown on Figure 3. The general coincidence of the residual positive anomaly with the higher parts of the mound is very close.

A cross section of the topography, with a 4 to 1 vertical exaggeration, is shown by the black area at the top of Figure 4 with the "Edge of Mound" corresponding to the outline on Figures 3 and 5 also indicated. This shows that the topographic feature is roughly co-extensive with the shallow part of the dome calculated to account for the negative residual gravity anomaly.

From the gravity analysis and relations to topography, we believe that the following are highly probable:

(1) The gravity anomaly is caused by a very large, shallow salt dome quite possibly, but not certainly, having a substantial overhang.

(2) The dome is shallow with a depth probably less than 2,000 ft deep and possibly very shallow.

(3) The dome probably is without substantial thickness of caprock.

(4) The shallow dome is genetically related to the topographic mound.

It seems probable that the details of the topography are the result of erosional or other processes such as have been the subject of comment and speculation by most of the earlier papers mentioned in the Introduction. One point seems worthy of comment in view of the present work. The central pinnacle, which, at its 60 ft depth contour, has dimensions of only about 1,000 by 2,000 ft, is so very small compared with the size of the mound as a whole and of the probable underlying salt dome, that it must have its origin in details of coral growth or of erosion which are not a direct consequence of the dome which is indicated by the geophysical work as the probable cause of the mound as a whole.

FAUNA

In two instances when the gravity meter was brought to the surface pieces of "coral" were found on one of the circular foot-plates of the instrument. These have been photographed and are shown in Figure 6. The "Brain Coral," Figure 6a, came from the pinnacle station, No. 49, at a depth of 72 ft. The Bryozoa, Figure 6b, came from station No. 18 on the north side of the pinnacle where the depth is 267 ft. The specimens were sent to Dr. J. Wyatt Durham at the University of California for identification. He reports that the specimen of Figure 6a "is *Deploria strigosa* (Dana), which is one of the species listed in Parker's paper"

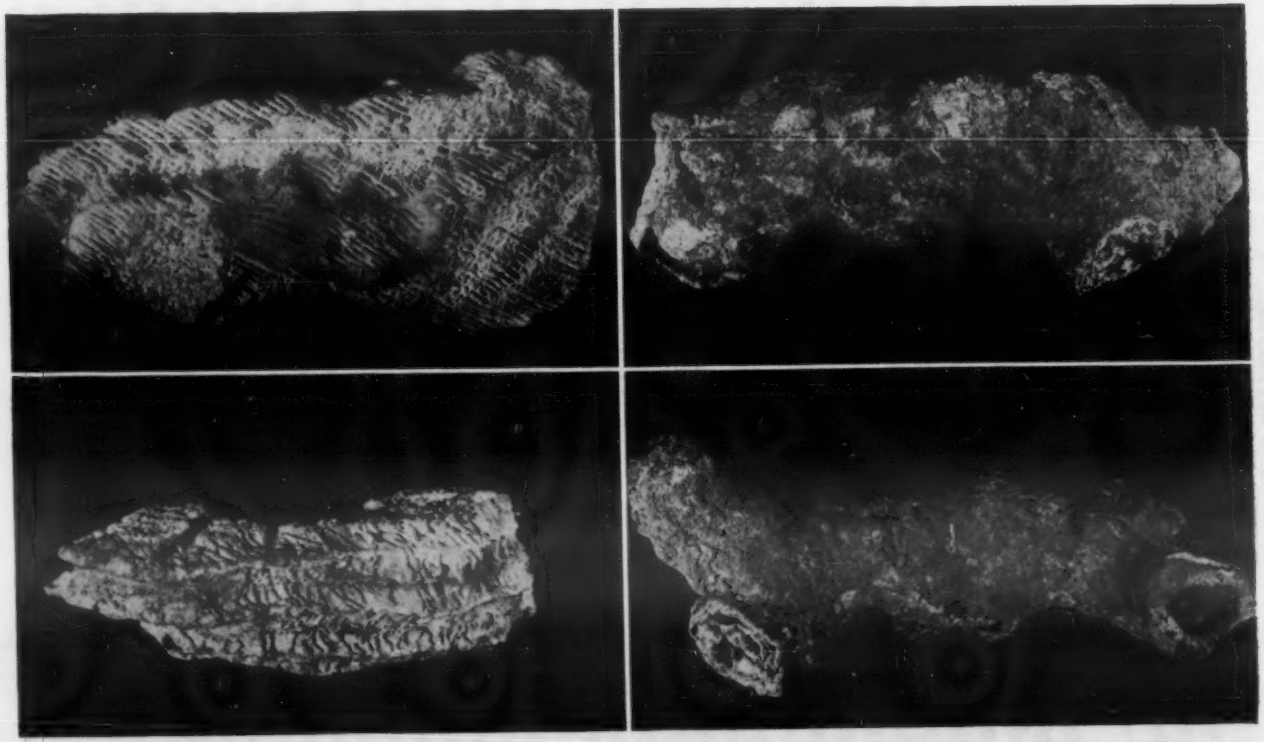

FIG. 6. Fossil forms brought up on gravity meter. Left: "Brain Coral" from station 49, on central pinnacle; water depth 72 ft. Right: "Bryozoa," from station 17, north side of pinnacle; water depth 276 ft.

and that the one of Figure 6b "is an irregular, crudely ramose mass of encrusting bryozoa. There are several genera and species represented, including *Cauloramphus* (?), *Hippaliosina* (?), a schizoporellid and at least two or three others."

SOME SPECULATIONS ON DOMES FAR OFFSHORE

The primary purpose of this paper is to present the results of the gravity survey and its analysis. The interpretation has given a strong indication that the mound "WAY" is coincident with a large, shallow salt dome. This naturally suggests relations with other salt domes within the geophysically explored part of the Continental Shelf and with other, generally similar, topographic mounds.

A recent study by Atwater (1956) indicates that, out to water depths of 100 ft off the Louisiana coast, the domes and structures occur with approximately the same frequency as on land.

Geophysical surveys have shown that domes occur with undiminished frequency out at least as far as water depths of 200 ft off the Louisiana coast. The single example shown by this survey suggests that the belt of frequent dome occurrence may extend to the edge of the shelf at about the 100 fathom (600 ft) depth contour. Off Louisiana, the area between the 100 and 600 ft depth contours is approximately the same as that between shore and 100 ft. However, the occurrence of topographic features on the sea floor does not correspond with the frequency of dome occurrence. There are many very shallow domes inside the 100 ft depth contour which have no recognizable topographic expression on one foot bottom contours which have been constructed from water depth measurements made in connection with detailed gravity surveys. Within this zone, any topographic expression is the exception rather than the rule. The relation of domes to topographic mounds near the edge of the Continental Shelf, indicated by this survey, suggests that conditions affecting the formation or preservation of topographic features change as the water becomes deeper. Two factors controlling this variation in topographic expression seem reasonable, i.e. (1) in shallow water, currents and deposition are more active, and either remove or cover up topographic features as they are formed, and (2) the deeper water may be more favorable for growth of rock-forming organisms.

The literature previously mentioned indicates differences of opinion as to possible relation of Continental Shelf mounds to salt domes. Carsey (1950), as previously mentioned, shows a chart (Fig. 23) indicating 164 mounds, of which 138 are east of longitude 94° or roughly off the Louisiana coast, and speculates (p. 376) that these may be underlain by salt domes. On the other hand, Gealy (1955) considers that domes have not been an important geomorphic factor on the topography on the Continental Slope. A large fraction of the mounds included in Carsey's count are between the 100 and 500 fathom contours and thus are on the "Continental Slope" as defined by Gealy.

It is our guess that the fairly regular, rather clearly defined mounds, which rise from a relatively smooth ocean floor, are those most likely to be caused by

domes. The mound surveyed and the next one east (East Flower Bank of Parker and Curry) are considered typical examples. A number of others, roughly along the 100 fathom contour, are indicated by Goedicke (1955, Fig. 1). Quite probably some, and possibly many of the closed highs in the more irregular topography of the Continental Slope are caused by processes of erosion or organic growth and are not related to salt domes.

If the other rather regular and roughly circular mounds near the break from Continental Shelf to the Continental Slope are large domes, similar to that inferred for the mound "WAY," we would have a linear belt of large domes which has no counterpart in the known Gulf Coast dome province, including both its on-shore and off-shore parts. Such a belt of domes may be localized by an active tectonic belt along the Continental Slope, as suggested by Weaver (1950, p. 357).

We have attempted to relate the marine seismograph work of Ewing *et al.* (1955) to these speculations. The line of the cross section (Fig. 18) southeast from Galveston (shown also with a somewhat more legible reproduction by Miller and Ewing (1956) page 413) passes rather near "WAY" and, as estimated from the small scale map, the mound is quite close to station 29 of that section. Station 29 indicates a speed of 17,200 ft/sec at a depth of about 15,000 ft. It may be possible that this speed represents the salt layer from which domes rise. It would be possible to calculate a salt form above this depth which would account for the gravity anomaly. The form would be very different from that shown in Figure 4. The overhang would not be present and the flanks of the dome would slope outward to permit the required salt volume above that depth. Such an interpretation would imply a reversal and axis of the Gulf Coast Syncline somewhere north of the edge of the Continental Shelf. That such an axis must be south of the shore line is indicated by the continuous south dip to the shore line and the indicated depth to salt there of the order of 30–40 thousand feet (Nettleton, 1952).

Alternatively the 17,200 ft/sec speed, which appears only at station No. 29 and the next one to the south, No. 28, where it is at shallower depth, may indicate the base of a thick Miocene wedge which is thinning to the south. That such a great Miocene wedge is not unreasonable is suggested by the fact that the deepest well ever drilled, near the Mississippi Delta, is considered to be still in Miocene at its bottom depth of some 22,500 ft. This alternative would require a great depth to the base of the salt column such as has been assumed for the calculated dome form.

It has been suggested (Oil & Gas Journal, 1956) that the shallow spines on the off-shore mounds might be useful locations for drilling platforms. However, if the domes are as large and as shallow as indicated by the gravity analysis, a well drilled on such a spine would find salt very shallow and probably could not be deviated far enough to reach the flank of the dome. This would be particularly true if the base of the salt is shallow and a much wider dome form were required to account for the gravity anomaly.

We have indulged in much speculation on the basis of one mound that ap-

pears to be over a salt dome. Obviously much more work is needed to determine the true nature of the outer rim of the Gulf Coast salt dome province. Similar gravity surveys over a number of other large mounds would show whether the one now surveyed is typical or exceptional. An old-fashioned refraction fan would indicate the size of the salt column to moderate depths and thus help materially to resolve the speculations as to depth of the base of the salt column. A radical difference in the form of domes related to mounds is indicated by the gross difference in the nature of the gravity pattern at "WAY" and that found by Allen *et al.* (1956) on the small spine "GUS" south of Galveston.

The writer is particularly indebted to his partners in Gravity Meter Exploration Company who supported the cost of this project. Thanks are due to La Coste and Romberg, Austin, who furnished the meter and repaired the damage and to offshore Navigation Co., New Orleans, who furnished the Raydist service and provided as special operator, Mr. J. Strayhorn, and to the boat crew, especially Mr. Beverly Bergeron, skipper, and Mr. Benjamin F. Collins, meter operator, to Dr. Marcus Hanna of Gulf Oil Corporation who made the photographs of the fossil specimens and to Dr. Durham for their identification.

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GEOPHYSICS, VOL. XXII, NO. 3 (JULY, 1957), PP. 643-645, 1 FIG.

CHART TO CHECK ELEVATION FACTOR EFFECTS ON GRAVITY ANOMALIES*

L. F. IVANHOE†

The effect of varying surface densities on gravity anomalies is a more common problem in areas of topographical relief than is generally recognized. There is an unjustified tendency to assume that gravity maps are unique and final, even though one basic assumption (density of surface rocks) is inherent in all gravity maps. The use of incorrect elevation factors will produce gravity anomalies over any topographic feature. Both positive and negative gravity anomalies can be produced by either a topographic hill or valley depending on the degree of error in the elevation factor. These "elevation factor anomalies" are especially troublesome on residual gravity maps. The interpretation of gravity data should always include an analysis of the elevation factor effect as well as a study of the surface geology.

Gravity maps are usually based on only one approximate elevation factor (Bouguer and free air corrections) over a fairly large area. The possible correlation on such maps between any particular gravity anomaly and the local topography can be most readily checked by use of a simple graph showing merely the amount the local anomaly could be changed by using a different elevation factor (Fig. 1).

This graph is based only on the Bouguer correction formula $0.01276\,\sigma h$(mg/ft) and does not include the free-air portion of the elevation factor, which does not vary with rock density. The series of straight lines indicate elevation factors due to different rock densities and the ordinates are elevation difference and net local gravity anomaly. Similar graphs can be easily prepared with any given elevation factor as the zero anomaly line.

The elevations to be used on the graph are only the net local elevation differences between critical stations and not elevations above sea-level. The type of topographic relief (valley or hill) must also be known to check correlation with the algebraic sign of the gravity anomaly. Elevation maps showing only the elevations of the gravity stations are most useful for determination of the net local elevation differences as well as to check surveying errors. Contouring of only those elevations actually used for gravity stations often reveals more obvious correlations between the elevations and gravity results than is apparent on more detailed governmental (USGS, etc.) contour maps.

It is a simple matter to determine an equivalent rock density from the chart if the gravity anomaly and elevation difference are known. If this density is the

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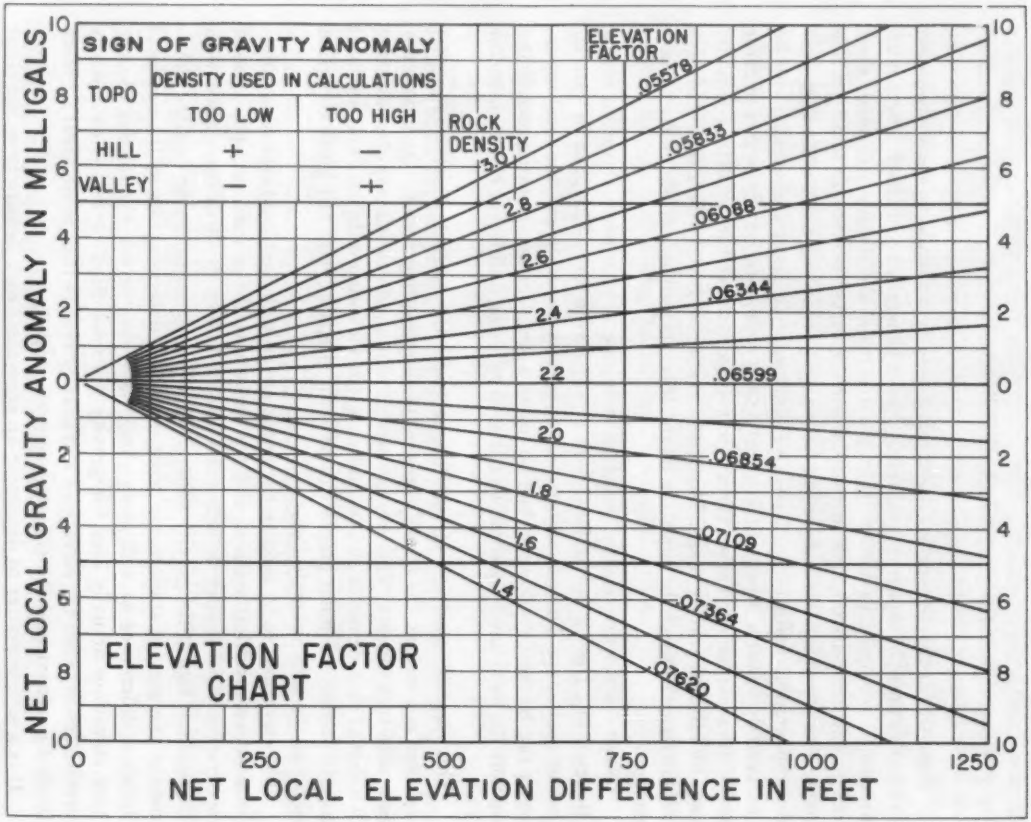

FIG. 1. Elevation factor chart.

same as of the outcropping rocks, then the gravity anomaly can be properly recognized as being merely due to the elevation factor and may be eliminated from further consideration. Any gravity anomalies which appear to reflect local elevation factor effects should only be accepted as geologically significant after careful study of all known factors.

ELEVATION FACTOR CHART

Example

Elevation factor originally used .06599 mg/ft

	Elev. (ft)	Gravity (mg)
Station 1	1,175	123.34
2	1,500	125.00
3	1,225	123.60

Station 2

Net local elevation difference

$$1{,}500-\left(\frac{1{,}175+1{,}225}{2}\right)=300 \text{ ft (Hill)}$$

Net local gravity difference

$$125.00-\left(\frac{123.34+123.60}{2}\right)=1.53 \text{ mg (+)}$$

Conclusion—From chart

If the topography here has a density of 2.60, then the entire gravity anomaly is due merely to the elevation factor effect. If this density does not appear to be reasonable for the surface rocks, then the anomaly must be due to other causes.

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GEOPHYSICS, VOL. XXII, NO. 3 (JULY, 1957), PP. 646–659, 6 FIGS.

IRREGULAR MAGNETIC ACTIVITY IN NORTHERN CANADA WITH SPECIAL REFERENCE TO AEROMAGNETIC SURVEY PROBLEMS*

K. WHITHAM† AND E. I. LOOMER†

ABSTRACT

An investigation of the diurnal and seasonal characteristics of irregular magnetic activity in northern Canada, using two indices of disturbance, shows that in general the *K* index provides a reliable but smoothed measure of short period activity. Two peaks of activity are evident, a day-time peak, dominant inside the polar cap, and a night peak, dominant south of the auroral zone. The latter occurs within one hour of local geomagnetic midnight at four Canadian observatories, whereas the day-time peak occurs progressively later at higher latitudes. The maximum activity occurs in the equinoxes at latitudes near the auroral zone, and during the summer solstice at very high latitudes.

Measurements of range at the most disturbed observatory suggest that aeromagnetic surveying in high latitudes is in general feasible, but that for accurate reconnaissance work it is very advantageous to plan operations, so far as conditions permit, taking account of the systematic diurnal variation of disturbance. It is shown that errors of about one half the assumed diurnal change between base lines will occur and sufficient data is given to allow approximate predictions of the optimum length of flight lines.

INTRODUCTION

There has recently been an increase in the use of airborne magnetometers in northern Canada for reconnaissance surveys in mineral and oil exploration, and it is evident from an examination of the areas presently surveyed, that this trend must continue. The magnetic anomalies mapped by this method can be used generally as an aid to geological mapping, or for specific purposes such as the estimation of basement topography and depth in oil exploration and the estimation of magnetic polarization anomalies in mineral prospecting. In direct interpretation the presence of larger anomalies produced by changes in intensity of magnetization in the basement is one of the difficulties to be overcome in interpreting the sharper and usually smaller anomalies produced by relief in the basement surface. Thus the accuracy of aeromagnetic contours required for oil exploration exceeds that for mineral exploration, and the problem of compensation for external transient changes in the earth's magnetic field is more important and difficult. As the auroral zone is approached, disturbance is much more pronounced in amplitude and frequency of occurrence than is the case at lower latitudes, and it would appear necessary to increase greatly the number of cross flight lines (base lines) and to restrict operations wherever possible to certain times during the day. The irregular disturbance appears to be highly differentiated in general, so that methods of compensation, using corrections based on records from ground magnetometers at a distant base, can be most unreliable and even misleading.

The Dominion Observatory has been approached on a number of occasions for

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advice on the magnitude and diurnal variation of the disturbance at various points in northern Canada, and the magnetograms from the Canadian observatories have been made freely available for inspection by exploration companies. In an attempt to give a general account of some properties of irregular disturbance, the authors have collected together here the available Canadian data on magnetic disturbance indices, and have with the aid of a new semi-quantitative index attempted to isolate the role played by a disturbance with a period and other characteristic time less than fifteen minutes. Quite definite diurnal properties have been demonstrated. At the most disturbed station a limited sample of data has been examined numerically in order to attempt approximate predictions. It should be clear that the results are statistical, and their use is warranted only in the case of an extended survey program. On any one day, the transient disturbance can depart significantly from its usual form, and, in the present state of geomagnetism, such days cannot be forecasted.

Several authors have described certain aspects of irregular disturbances, but the relationship to aeromagnetic surveys at high latitudes is not always clear. However, Morley has discussed data obtained from ground stations 130 miles apart N–S and 87 miles apart E–W near the auroral zone. He showed that when one station is used to control a survey flown over the other, there is no appreciable reduction in the errors from the case when no ground control is used, and linearity is assumed over ten minutes flying time between base lines. In both cases it was concluded that useful information could be obtained in the auroral zone over shield areas, but such maps would be of doubtful value for oil survey work. Morley's region was centered about 63° N geomagnetic, and is on the southern side of the maximum auroral zone. In view of the existence of the sedimentary basins of western Canada extending well into the sub-Arctic and of thick sedimentary beds overlying many of the Arctic Islands, it seems worthwhile re-examining these conclusions using data obtained from several locations and taking into account any diurnal properties of disturbance.

LOCATION OF THE CANADIAN OBSERVATORIES

Figure 1 shows the positions of the four Canadian permanent magnetic observatories together with the north geomagnetic and dip-poles, and the approximate position of the center of the auroral zone, following Davies (1950). It is obvious that Meanook (geomagnetic latitude $\Phi = 61.8°$ N) and Baker Lake ($\Phi = 73.7°$ N) are south and north respectively of the zone of maximum auroral frequency, whereas transient disturbance at Resolute ($\Phi = 83.0°$ N) is typical of conditions inside the geomagnetic polar cap. These three stations are therefore well situated for demonstrating the latitude variation of disturbance along the geomagnetic meridian, $\Lambda = 60°$ W, approximately. The circles in Figure 1 show the location of additional observatories which will be in operation during the International Geophysical Year, 1957–58 and the crosses show additional locations where fluxgate recording magnetometers will be operated.

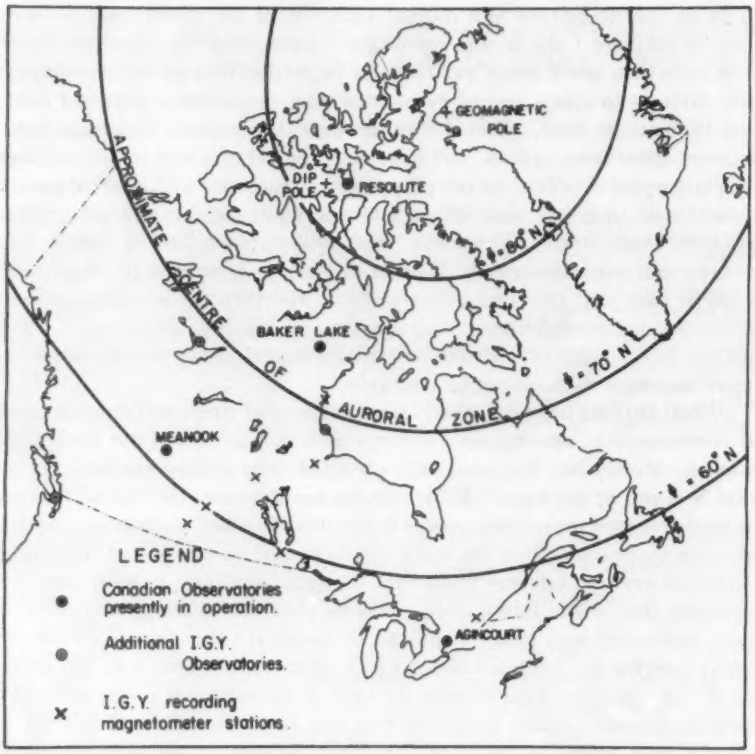

FIG. 1. The location of the Canadian magnetic observatories and the auroral zone in Canada.

SEASONAL AND DIURNAL VARIATIONS OF THE K-INDEX ALONG LONGITUDE $\Lambda = 60°$ W

Three component magnetograms are available for Resolute from October, 1953 and for Baker Lake from 1951. Figure 2 shows the diurnal variation of the K index for the three seasons for 1951–54 inclusive at Baker Lake and Meanook and for 1954 at Resolute. The K index is a three hour range index which characterizes the variation in the degree of irregular magnetic disturbance produced by solar corpuscular radiation, and has been adopted as the standard magnetic activity index by the Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics since September, 1939. It has been defined and discussed by Bartels, Heck and Johnston (1939). 1954 was a year of sunspot minimum, and the four years 1951–54 represent the declining portion of the last sunspot cycle.

In Figure 2 the times of local geomagnetic noon and midnight in the different seasons are shown with marked arrows. At Meanook, the dominant feature is a

flat night-time maximum near local geomagnetic midnight. A large seasonal variation with a maximum in the equinoxes and minimum in the winter solstice is evident from the curves. At Baker Lake both a daytime and night-time maximum of disturbance are evident in the *K* curves, the daytime feature being dominant. The smoothed times of maximum activity are then approximately 3 hrs before local geomagnetic noon, and near local geomagnetic midnight. The flat daytime maximum remains substantially the same in amplitude and position in each season, whereas the secondary night-time activity shows a seasonal variation

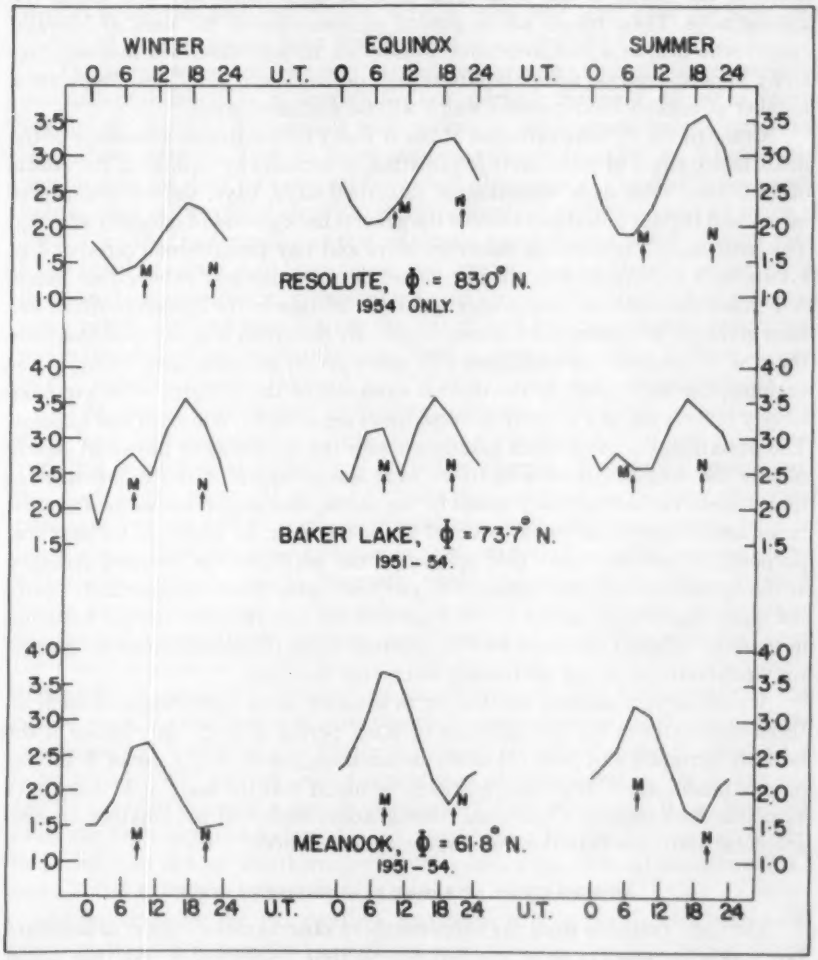

FIG. 2. The diurnal variation in the *K* index during three seasons at three northern observatories.

in amplitude and phase similar to that of disturbance at Meanook, previously described. At Resolute there is a dominant daytime maximum only in all seasons, with a daily maximum approximately 2 hrs before local geomagnetic noon, and with the disturbance reaching a maximum in the summer months and a minimum in the winter months.

It is evident that the night-time activity has a maximum in the equinoxes, whereas the daytime activity has a maximum in the summer season. The former is dominant south of the auroral zone, and its influence can be seen somewhat north of the center of the zone. The latter is most important well inside the auroral zone. These results are in general agreement with the work of Mayaud (1956) who has, in a comprehensive world-wide review, described magnetic activity in polar regions, using amplitude data derived from *K* indices. There are a number of notable discrepancies which will be discussed later.

Although the diurnal variation of the *K* index is valuable as a measure of the disturbance effect of solar particle radiation, it includes by definition the effects of additional solar daily variation on disturbed days, bays, sudden commencements and regular pulsations besides the general background of irregular activity. The solar daily variation on disturbed days and bay phenomena correspond to events with a characteristic time or period between one and twenty-four hours. A detailed discussion of such properties of disturbance in the Canadian Arctic has been given by Whitham and Loomer (1956). By definition it is not clear therefore that the *K* index can be associated with short period magnetic activity only. For example, the night peak in the diurnal variation of the *K* index at Baker Lake largely reflects the bay activity at these times reported by Whitham and Loomer. The pulsational activity often associated with the beginning of bays and clearly seen in the magnetograms is likely to have less influence on the *K* measures at these times. Yet such activity would be one of the most important sources of error in an aeromagnetic survey conducted at those times. In addition, for practical purposes in a survey where field operations can only give the required accuracy at the optimum times, the influence of 3 hr smoothing is not unimportant. Lastly the quasi-logarithmic nature of the scale and the fact that the diurnal variation in range of different elements may be different make the identification of the vector characteristics of the perturbing force very uncertain.

Accordingly, it seemed worthwhile to examine some magnetograms from all three observatories for the influence of short period activity only to see if the latitude variation and patterns of disturbance suggested by the use of *K* indices require modification. It should, however, be noted that the body of *K* index data available does represent the most homogeneous source of information on geographical and time variations of magnetic disturbances.

AN S-MEASURE OF SHORT PERIOD DISTURBANCE

The data available from the three northern observatories consist of standard run magnetograms (15 or 20 mm/hr) and so time resolution of less than about one to two minutes is not possible.

To describe activity in the range one minute to one hour or so, several different approaches are possible. For example, the magnetograms can be examined for certain well defined events with periods in a defined interval and characteristic amplitude properties: giant pulsations with a shuttle-shaped envelope form such a class. Alternatively the spectrum of frequencies less than about one per minute can be investigated using such statistical tools as correlogram or periodogram analyses, or quick run records, of the sort not available from the Canadian observatories can be examined for the mean frequency and amplitude at different times. The short period ranges can also be measured by sampling, and their statistical properties and distribution defined. This has been done for a limited sample of data at Baker Lake and the results are described later.

These methods all require very careful measurement and varying amounts of mathematical labor. It is simpler for our purpose, however, to use a coarse logarithmic index of disturbance with periods or other characteristic times less than fifteen minutes. Such an index can conveniently be called an S index, and was used on the data for one year from each observatory. The maximum amplitude in (any of) the three elements was measured for each hour, and an index of $S=0, 1, 2$ assigned according as this maximum was 1 gamma or less, greater than 1 and equal to or less than 10 gammas, and greater than 10 gammas respectively. Because the scale is coarse, measurements are very quickly obtained whereas the mean values obtained from a large amount of data reflect quite well the diurnal properties of short period disturbance. Figure 3 shows the results in three seasons from November, 1953 to October, 1954, a year of minimum sunspot activity.

At Meanook, daytime and night-time peaks are evident in S whereas only a night-time peak appears in K (Fig. 2). The night-time peak shows a seasonal variation in agreement with the K variation whereas the daytime peak is predominant in the winter. It is clear that the daytime peak occurs near 0800 local geomagnetic time, and the night-time peak near 2300 local geomagnetic time on the average. There are thus two classes of short period activity, one associated with the bay activity near geomagnetic midnight, and contributing to S and K with a seasonal maximum in the equinoctial months and minimum in the winter months and a second later morning maximum which is the dominant feature in the winter months only. The frequency distribution of hours with $S=0$ has a diurnal maximum near the night-time maximum in S. This implies that on disturbed days, the amplitude of disturbance is generally more nearly equal at the two times than is indicated in Figure 3. It is not obvious that the S index and K index are highly correlated from a comparison of curves, but in fact in any one day they are: for example, a sample calculation for the winter months at Meanook using the arbitrary parameters $\sum_{\text{day}} K$ and $\sum_{\text{day}} S$ for the day gave a correlation coefficient of 0.93. Furthermore Figure 4 shows the seasonal variation in the mean S and K indices to be very similar as one might expect.

At Baker Lake, the flat daytime maximum with a peak about 0900 local geomagnetic time is dominant and shows little seasonal change. The night-time maximum near local geomagnetic midnight shows a seasonal minimum in the

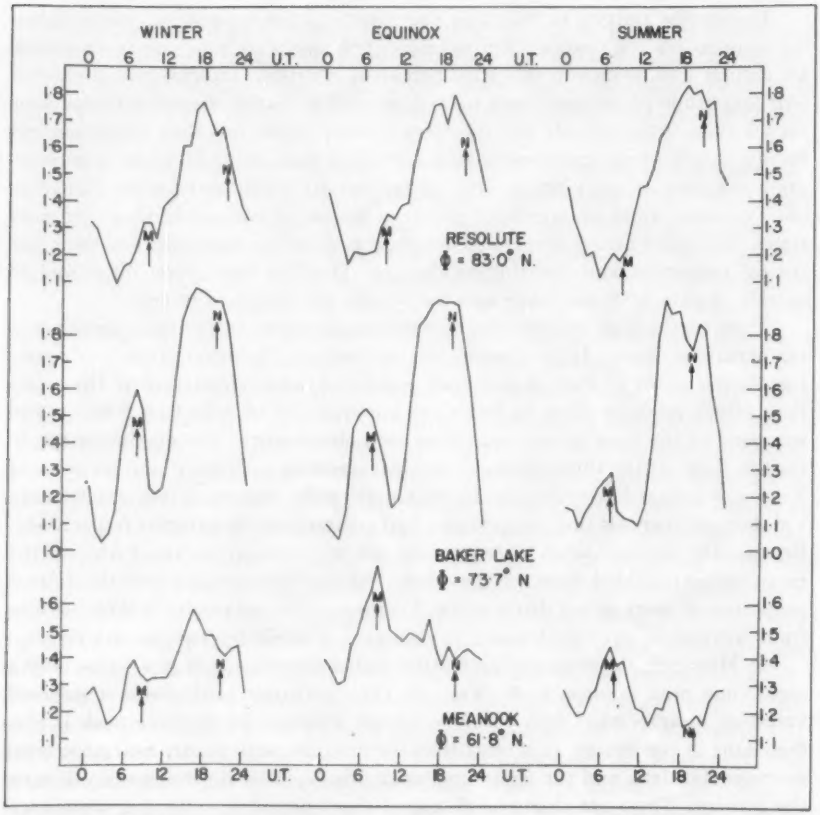

FIG. 3. The diurnal variation in the S index during three seasons at three northern observatories.

summer months. It should be noted that the logarithmic value of the scale used tends to emphasize the difference in amplitudes between the two maxima. Furthermore, this difference on the average is exaggerated because the number of very quiet hours has a diurnal maximum near the night-time maximum in S. In Figure 4 close seasonal correspondence between the two indices S and K is clear. In practice, it should be added, the measurements of S at Baker Lake were restricted to the Z magnetograms. This was primarily a matter of convenience since the Z sensitivity was much lower, and is not believed to affect qualitative comparisons.

At Resolute, the S curves also closely follow in form the K curves, and reach a flat maximum two to three hours before local geomagnetic noon. The maximum in both S and K appears earlier in the winter months, but the significance of this result in view of the flatness of the peaks is not certain. However, it appears

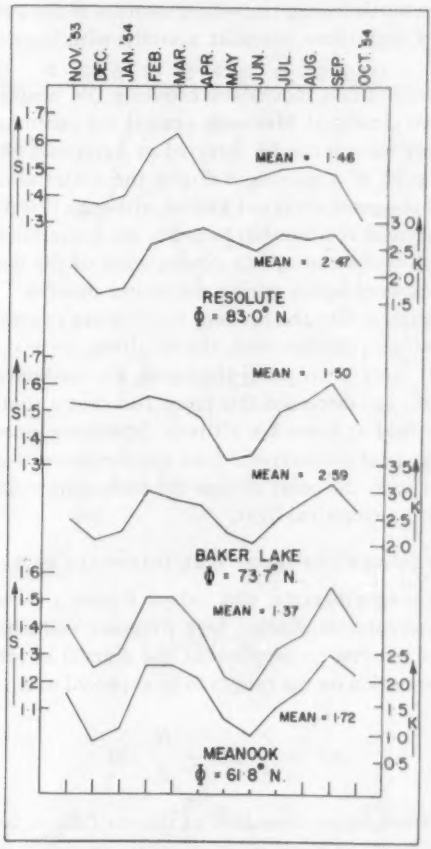

FIG. 4. The seasonal variation in the mean S and K indices at three northern observatories.

likely that in the winter months, a very slight evening maximum develops close to magnetic midnight, this might be expected from the known night-time maximum in bay activity during the winter months at Resolute (Whitham and Loomer, 1956), although such activity is too weak to reflect in the K index. Finally the level of S activity reflects the customary summer, equinox, winter order inside the polar cap, but the seasonal variation in S activity appears to be much less than that reflected in the K index.

In conclusion, the above data indicate that south of the auroral zone the night-time peak is dominant and the activity corresponding to this peak moves northerly during the winter months, and can then be distinguished along with a dominant daytime peak. This would be expected as a consequence of the move-

ment several degrees north during the winter months of the auroral zone, in view of the association of night-time irregular activity with bays and both of these with visual aurora.

The daytime precipitation moves south during the winter months, and can then be distinguished clearly at Meanook against the customary night activity. In fact, this southerly motion can be detected at Agincourt ($\Phi = 55°$ N), where a subsidiary daytime peak of K is evident during the winter months. The explanation of this seasonal phenomenon is not known, although it is presumably either a matter of the geometrical relationship between the incoming solar particles and the earth during different seasons, or a consequence of the decrease of shielding effects of lower ionosphere layers during the winter months.

It should be remarked that the times of maxima are referred to local geomagnetic noon and midnight, though with the longitude separation and this small number of stations, there is no proof that such a co-ordinate representation is valid. Mayaud (1956) has discussed this point and shown that a co-ordinate system referred to the field at 5,000 km altitude provides a smoother fit to world-wide data. However, local geomagnetic time approximates this parameter better than local time, and from the point of view of aeromagnetic surveying the curves are best regarded in an empirical light.

AVERAGE RANGES OVER SHORT TIME INTERVALS AT BAKER LAKE

Examination of magnetograms, and indeed Figure 3 shows that among the three Canadian observatories studied here irregular disturbance is greatest at Baker Lake. It is of interest to supplement the diurnal information of Figure 3 with numerical information on the ranges to be expected over short time intervals and since

$$\Delta F = \frac{Z}{F} \cdot \Delta Z + \frac{H}{F} \cdot \Delta H$$

and Z/F is sixteen times larger than H/F at this latitude, it is clear that $\Delta F \doteqdot \Delta Z$ and numerical data based on the Z magnetograms provide a good approximation to the perturbation in total field, F.

As a guide in the aeromagnetic survey problems the magnetograms were sampled, and the change in Z measured for given periods of time. Initially two samples of 28 days each in July, 1954 and July, 1955 were measured every $2\frac{1}{2}$ minutes of time (standard run magnetograms 15 mm/hr speed were available and $2\frac{1}{2}$ minutes of time represents about the minimum time interval feasible in this kind of work). The diurnal variation of the average displacement of the Z trace (independent of sign) was calculated and is shown at the bottom of Figure 5 plotted against local time. The solid line represents the mean of the results for the two samples, and individual points for the two samples are shown. It is clear that the diurnal amplitude in 1954 exceeds that in 1955. The two maxima in Figure 5 fall at the times mentioned earlier in the discussion of S. The changes in

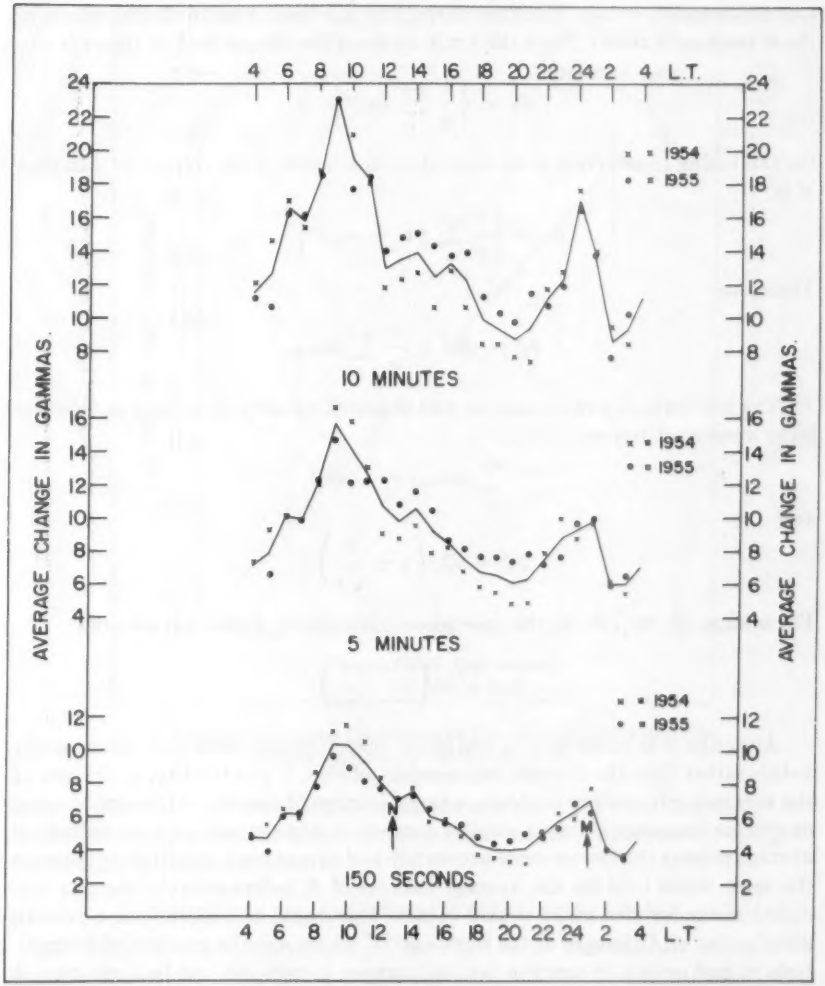

FIG. 5. The diurnal variation of the change in Z at Baker Lake during $2\frac{1}{2}$, 5, and 10 minutes of time.

Z can be combined algebraically and the mean displacements independent of sign found during 5 minutes, 10 minutes, etc. The corresponding diurnal variation curves for these longer intervals are also shown in Figure 5. Running means can be taken, or combination in pairs, etc., made. The latter halves the arithmetic at the expense of halving the number, and was the process adopted.

The results found agree well with the predictions of elementary theory for

root mean square values. Consider during any one hour, a set of displacements of the Z trace α_i in time t. Then the r.m.s. value of the change in Z in time t is

$$\beta_1 = \left\{\frac{1}{n}\sum_i (\alpha_i)^2\right\}^{1/2}.$$

On combining in intervals $2t$ we have the r.m.s. value of the change in Z in time $2t$ is

$$\beta_2 = \left\{\frac{1}{n}\sum_i (\alpha_i + \alpha_{i+1})^2\right\}^{1/2}.$$

Therefore

$$\beta_2^2 = 2\beta_1^2 + \frac{2}{n}\sum_i \alpha_i\alpha_{i+1}.$$

The last term can take positive and negative values and so for a sufficiently large number of terms

$$\sum_i \alpha_i\alpha_{i+1} \sim \sqrt{n}\beta_1^2$$

and

$$\beta_2^2 = 2\beta_1^2\left(1 + \frac{1}{\sqrt{n}}\right).$$

For n large, $\beta_2 \to \sqrt{2}\,\beta_1$. In the case when non-running means are adopted

$$\beta_2 = \sqrt{2}\beta_1\left(1 + \frac{1}{\sqrt{2n}}\right).$$

Although it is customary in statistical theory to deal with root mean square values rather than the average, independent of sign, it was felt that in the case of the aeromagnetic survey problem, a large number of smaller values are of equal or greater importance than a smaller number of large values, and the numerical average reflects the former more accurately and so was used. Apparently however the same ratios hold for the average changes of Z, independent of sign, as predicted above for root mean square values. This would be expected for a smooth distribution of Z changes of the form $n\alpha e^{-Bx^\mu}$ where n is the number with amplitude x, and $\mu \sim 0.5$ in practice for the changes in two and one half minutes. A distribution of this type provides a good empirical fit to the data. The ratio of the value of each successive diurnal curve, showing the average value of the change in Z for a given time interval for each hour of the day and obtained by combining consecutive Z changes, to the diurnal curve for displacements in 150 seconds was calculated, together with its dispersion in the twenty-four one hourly intervals of the day. The results are shown in Figure 6 in a log—log plot for time intervals of 5, 10, 20, and 60 minutes, and agree well with the predicted curve for r.m.s. values, even to time intervals of one hour. It is concluded that a random

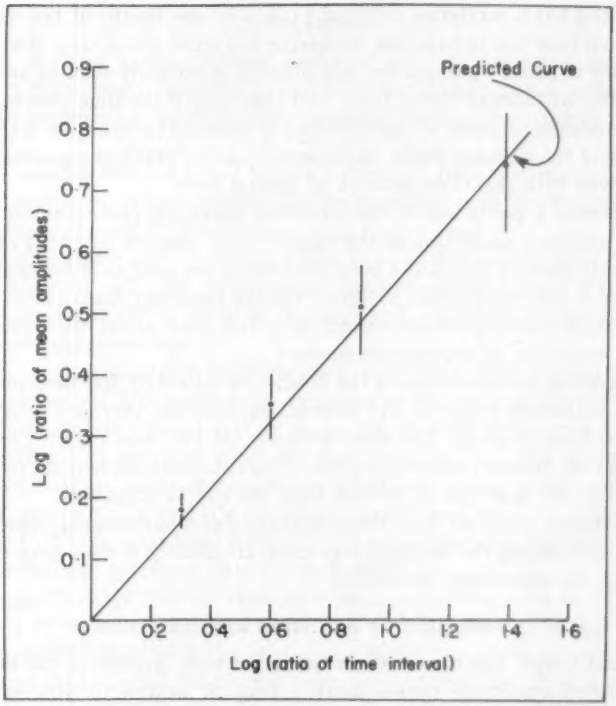

FIG. 6. The relation between the changes in Z in different intervals of time and the durations of the time intervals.

walk solution is a good empirical fit to the data, even up to time intervals of one hour. Ultimately persistent longer period features would produce severe disagreements with this random picture.

APPLICATION TO CORRECTIONS FOR TRANSIENT CHANGE

At low latitudes 25–50 mile flight lines (10 to 20 minutes) are often flown because these are least fatiguing to the operator and the diurnal variation error in 10–20 minutes is usually small, after correcting the flight line by assuming a linear change with time and fitting the base-line values.

Applying the simple concepts outlined above, it can be seen that if the time duration of a flight line is $2\frac{1}{2}n$ minutes, and at the given time of day, the average change in $2\frac{1}{2}$ minutes is x gammas, an average change of $\sqrt{n}\,x$ gammas would be expected between corrected base lines. At any point $2\frac{1}{2}m$ minutes from the first base line, a correction of $m/n\sqrt{n}\,x$ gammas would be applied assuming linearity whereas the average displacement is $\sqrt{m}\,x$. The difference is $(\sqrt{m}-m/\sqrt{n})x$

gammas, and has a maximum value of $\frac{1}{4}\sqrt{n}\ x$ or one fourth of the diurnal correction from base line to base line. Referring to Figure 5, it is clear that results to an accuracy of about 1 gamma are only possible in the early evening and morning hours at the latitudes of Baker Lake, and then only if the time interval between base lines does not exceed $2\frac{1}{2}$ minutes (say 6 miles). The situation is three times worse during the morning hours, and results to an accuracy of 3 gammas only are possible even with this close network of control lines.

In this way a prediction of the minimum operating procedure for closure is possible, besides a prediction of the magnetically quietest intervals of the day. In general it appears that if the same procedures are used as in lower latitudes it is doubtful if the corrections for diurnal change assuming linearity between base lines 25 to 50 miles apart are correct to better than about ten gammas. This would be serious in oil exploration surveys.

This approach underestimates the difficulties caused by transient disturbance, since the maximum range in any interval exceeds the average change of force during the time interval. The ratio between the two was 1.9 ± 0.3 in one trial determination. Hence it seems likely that errors of about one half the total diurnal change from one base line to another base line can be expected.

Furthermore it is clear from the examination of many magnetograms that the periods found during the morning maximum are usually shorter than those present during the night-time maximum.

VARIATION OF INTENSITY WITH LATITUDE

Mayaud (1956) has discussed the variation with latitude of the intensity of the smoothed amplitude ranges derived from K indices in different seasons. From his curves it can be seen that the maximum in activity anywhere in northern Canada is not likely to have a diurnal range exceeding two times that measured from the Baker Lake magnetograms, and the level of activity at the quietest time of the day is not likely to exceed that at the Baker Lake quiet time by more than about 10 percent. Simple calculations based on line or sheet currents and a dipole field distribution are possible, and these show that no matter how complex the current distribution is in the ionosphere near the auroral zone it is unlikely that the maximum perturbations in F can exceed those at Baker Lake by a factor of more than two. In practice, moreover, examination of the magnetograms indicates that the larger perturbations are in the horizontal components at all three stations, but particularly so at Resolute inside the polar cap. Hence the current sources largely contributing to the irregular activity are approximately overhead, and the S curves in Figure 3 can be regarded as indicating the latitude variation of those sources. It is then evident that the daytime peak seems to correspond to a maximum precipitation on the northern edge of the auroral zone and well inside the polar cap (weak solar streams); this precipitation moves south during the winter season. The night-time peak corresponds to precipitation nearer the auroral zone, and in the winter season moves substantially to the north.

CONCLUSIONS

1) The daytime and night-time peaks of activity suggested by Mayaud (1956) have been clearly identified in northern Canada using an *S* index in which only disturbance with a period or other characteristic time less than 15 minutes is measured.

2) The usual *K* index is found to give a good but smoothed representation of irregular disturbance of short period, despite the existence of bay-like phenomena and the enhanced solar daily variation on disturbed days.

3) The night-time activity occurs with a maximum within about 1 hr of local magnetic midnight and is the dominant feature immediately south of the auroral zone, less important to the north of the zone and negligible (except possibly in winter) inside the polar cap.

4) The daytime maximum occurs several hours before local geomagnetic noon at all three locations, but is primarily dominant to the north of the auroral zone. This maximum is very broad and produces the greatest difficulty in aeromagnetic surveying. The optimum times for summer surveys at high latitudes from this point of view are in the few hours near local noon south of the auroral zone, and in the early morning and late evening hours north of the zone. Theoretically it would be best to fly near local midnight well inside the zone. However, Figures 2 and 3 contain the necessary data for such predictions.

5) It appears likely that the changes in total perturbing force at Baker Lake occur with a certain distribution of values and with random sign so that it can be shown empirically that with the customary flight procedure in aeromagnetic survey, errors of about half the diurnal correction between base lines, are likely to appear in the individual profiles. It can then be easily demonstrated from magnetogram measurements that the accuracy required for oil survey work can only be achieved with very short flight lines, and by flying at the magnetically quiet times of day.

ACKNOWLEDGMENTS

We wish to thank Mr. R. G. Madill for his advice and encouragement, and the representatives of a number of aeromagnetic survey companies, who first brought this problem to our attention.

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GEOPHYSICS, VOL. XXII, NO. 3 (JULY, 1957), PP. 660–687, 17 FIGS.

PROSPECTING FOR GROUND WATER BY INDUCED ELECTRICAL POLARIZATION*

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ABSTRACT

When direct current introduced into the ground at two points is interrupted, a small voltage, which may take several minutes to decay, appears between another pair of electrodes. This effect, called by C. Schlumberger "provoked polarization," is found useful in prospecting for ground water. Laboratory experiments indicate that induced polarization (I.P.) depends on cation exchange in the clay minerals contaminating the aquifers. It is suggested that the effect is due to electrodialysis of the clay within the aquifer, which acts as a distributed electronegative membrane. The magnitude of the I.P. depends on the kind of clay and the kind of positive ions in the water. It is inversely proportional to the conductivity of the water and independent of the kind of negative ion dissolved therein. The rapidity with which the I.P. decays appears to depend only on the grain size of the aquifer. Field trials and experiments on laboratory models give promise of useful application of the method to depths of about 350 feet.

INTRODUCTION

Experiments on detection of ground water by induced electrical polarization were begun at the New Mexico Institute of Mining and Technology in the fall of 1953. Since that time both laboratory and field work have been continued at a steady pace. Although this investigation has been reported at meetings and during a lecture tour to some local chapters of the SEG, publication of an article was postponed until the mechanism of the polarization phenomenon became more fully understood. Publication at this time is prompted by the promising results obtained in the field and by the realization that a complete explanation of the phenomenon is not likely to be forthcoming in the near future.

Conrad Schlumberger (1930) was aware of the electrical polarizability of moist ground prior to 1920. Like his present followers, Bleil (1953) and Brant (1953), Schlumberger wanted to prospect for a metallic ore body by conducting direct current into the ground, interrupting it, and observing the decay of the voltage picked up at two other electrodes. To his distress, Schlumberger found that the effect from wet soil completely masked the effect he expected to get from the sulfide. He called this "provoked polarization" and correctly remarked that the observed voltage does not originate at the electrodes, but is a volume property of the earth, the polarization being generated instantaneously at great distances

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and being proportional both to the intensity of the charging current and the duration of time it is made to flow. Examples of more sophisticated transient electrical prospecting, such as "Elflex," described by Evjen (1948), and the patents of Potapenko (1940) are aimed at prospecting for petroleum. Ours is the first attempt to use induced electrical polarization as a method for finding ground water.

LABORATORY INVESTIGATIONS

In water-saturated sandstone or alluvium, induced polarization appears when the surfaces of the sand and gravel are partially coated with a film of clay. Clean quartz sand saturated with water shows almost no effect. A clay slurry likewise is unpolarizable; so also is the mixture obtained by adding dry sand to the slurry, such that the latter fills the pores between the sand grains. After this mixture is dried, however, and then saturated with water, it becomes polarizable and stays so indefinitely. Presumably, drying coats the sand grains with clay; on subsequent wetting, the clay does not disperse into the pores between the sand grains but covers them with a stable film necessary for the appearance of polarization.

Various sand-clay mixtures saturated with many different electrolytes were studied with the apparatus shown in Figure 1. A 200-gm sample consisting of sized quartz sand, with a few percent of clay mineral, is placed into a bakelite trough or glass tube and saturated with a weak aqueous solution. Usually the solution is slowly percolated through the sample until the clay reaches equilibrium with the solution. This process may take several days and require several liters of solution. The flow is stopped before electrical readings are taken. Equilibrium is indicated when the polarization and the resistivity of the specimen remain the same 24 hours after the flow is stopped. In taking measurements, the rheostat R_2 is adjusted to nullify any residual electrode potentials. Then, by depressing the switch to position 1, direct current is made to pass through the specimen for a fixed length of time, at the end of which the switch is snapped to position 2, connecting the direct-coupled amplifier to the nonpolarizing potential electrodes a few milliseconds after the current circuit is opened. A voltage-decay curve is recorded. The area under this curve can be calculated from the record, or it can be measured by an electronic integrator. The latter method was used in much of our earlier work, but recently we have used only the decay curves in data analysis. The resistivity of the sample can be computed from the high-resistance voltmeter V and the ammeter I.

Some details of the apparatus and of the experimental procedures will be mentioned for the benefit of those who may want to duplicate them.

Convenient sample holders are made of linen bakelite tubing, 2 inches o.d. and 1.5 inches i.d. A 9-inch length of tubing is cut along a diameter. The two halves are fitted with square bakelite ends, forming two troughs, which then are impregnated in a hot bath of ceresin wax. The solution can be percolated through the trough by means of tubing waxed in the ends. To avoid drying the specimen,

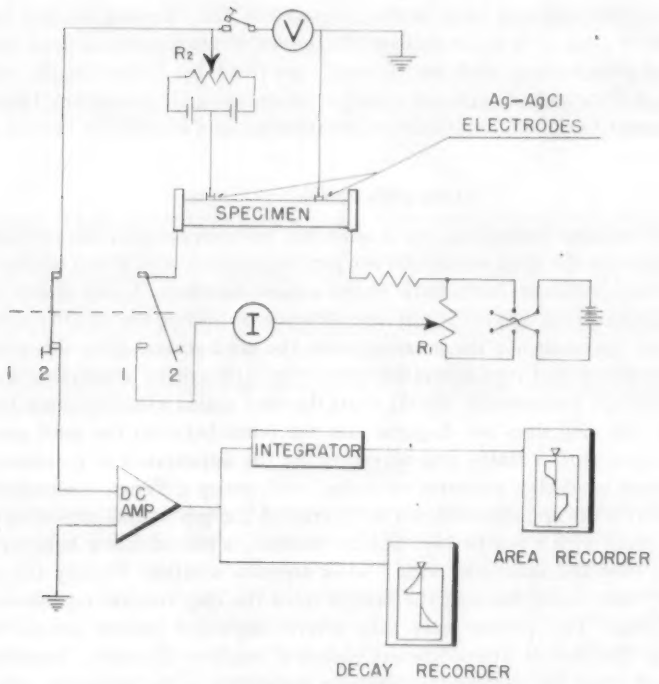

FIG. 1. Circuit diagram of laboratory apparatus.

the trough is covered with a plate glass lid when not in use. Between 100 and 200 gm of a mixture of sand and clay usually is poured dry into the trough. It is shaken down after wetting to produce uniform packing.

The current electrodes are usually of platinum foil and are simply shoved into the mixture at the ends of the tray. The potential electrodes are Norton alundum filter cups, type R. A. 98 B/P 5204, rendered impervious by plastic spray, except for a strip about 3/32 inch wide on the bottom surface. The cups are filled with silver chloride paste and an excess of distilled water. The electrical connection to the amplifier is made through a piece of silver foil dipping into the paste. Because of the low solubility of the silver chloride and the relatively large ion concentrations in the specimen, the slight amount of leakage from the electrodes does not produce spurious effects. The cups are merely set on the surface of the specimen, with the permeable streak normal to the axis of the trough and about two inches from the ends of the trough. These nonpolarizing potential pots can be used with sulfates, carbonates, phosphates, and probably other anions, as well as with chlorides. For chlorides only, one can use silver wires coated with

a porous layer of silver chloride. These potential electrodes are convenient because they can be sealed in specimen holders made of glass tubing. To test the electrodes, measurements are made on the trough just filled with electrolyte or with clean quartz sand saturated with the electrolyte.

A convenient amplifier-recorder combination is the Varian model G-10 chart recorder, which can be connected directly to the potential electrodes. A more flexible arrangement is a Kay Lab microvoltmeter, model 202, followed by a Varian or an Esterline Angus recorder. If the Varian recorder is used, the output from the Kay Lab microvoltmeter should be divided 100 to 1. In the case of the Esterline Angus recorder, a power amplifier needs to be inserted between the microvoltmeter and the recorder because, if the connection is direct, the low output impedance of the amplifier overdamps the recorder.

Several methods have been used to prepare the specimens. Weighed amounts of clean sand and powdered clay mineral can be mixed dry by tumbling. Apparently, during the mixing process, clay particles stick to the sand grains, so that when the specimen is wet, it exhibits polarization immediately. Sometimes the procedure is to wet the specimen with distilled water, let it dry, and then introduce the electrolyte under investigation. It should be remembered that some hydrogen clays are altered by drying (Grim, 1953, p. 143). If the clay makes a homogeneous slurry, it can be forced through the sand with an aspirator. After the passage of the slurry the aspirator dries what is left on the sand grains. The resulting cake is then broken up for filling the specimen holders.

In quantitative laboratory experiments, it is essential to make sure that the clay mineral is in a known condition at the start of the experiment, and that it is in equilibrium with the electrolyte at the time of measurement. One can start with either a hydrogen- or an ion-saturated clay. To put the clay into the hydrogen form, the clay either is electrodialyzed, or a 0.1-normal solution of HCl is percolated through the specimen for a day or so. A strong salt solution can be used to saturate the clay with a particular metallic ion as long as the solution does not contain sodium or potassium. In the case of sodium and potassium, dispersion of the ion-saturated clay occurs when dilute solutions are introduced later into the specimen.

A typical set of voltage-decay curves taken in the laboratory is shown in Figure 2 for excitation times ranging from 1 to 120 sec. The ordinates are in millivolts divided by the voltage appearing between the potential electrodes during the passage of the energizing current. The material was 20- to 30-mesh quartz sand treated with a three-percent montmorillonite slurry. The sand was dried after treatment, placed in the holder, wetted with distilled water, dried again to fix the clay on the sand grains, and percolated finally with a 147-ohm-meter NaCl solution. In comparing data several quantities read from the curves can be used. Much of the early work was done by comparing the areas under the voltage-decay curve. Recently we have been tabulating the ordinates at two times, such as 5 sec and 20 sec after the current is shut off. By taking the ratio of

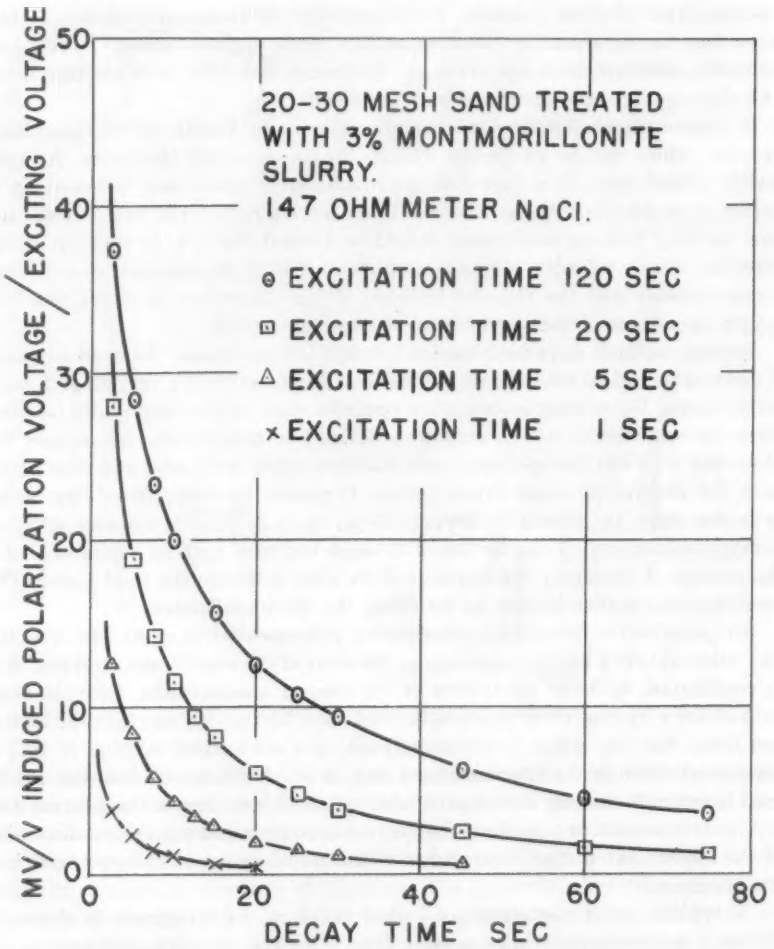

FIG. 2. Voltage-decay curves for 20- to 30-mesh sand coated with montmorillonite.

the two ordinates, some measure of the rapidity of the voltage decay is obtained. The polarizability of a given mixture of sand clay and electrolyte is independent of the voltage gradient. In Figure 3 the polarizability, measured as the area under the decay curve in millivolt seconds divided by the potential difference in volts that existed between the potential electrodes when the charging current was passing, is plotted against the excitation time. The experiment was performed in a trough 30 ft long and about one square inch in cross-sectional area, with 1- and

3-percent mixtures, by dry weight, of bentonite in sand. Within the limits of experimental error, data for voltage gradients differing by as much as a factor of 500 fit the same curve. For a given specimen and excitation time the induced polarization is exactly proportional to the density of the charging current. The same is true for the voltage between the potential electrodes when the current is flowing. Dividing the observed polarization by this voltage yields the polarizability of a medium—a constant property for a given resistivity and excitation time.

The dependence of the magnitude of the induced polarization, expressed as the area under the voltage-decay curve per volt of excitation, on the time of excitation is plotted in Figure 4 for three materials, namely, an ion-exchange resin in sand, a three-percent laboratory sample of bentonite, and the alluvium of the Rio Grande Valley *in situ*. The sample of bentonite and the natural alluvium give straight lines of the same slope on log-log paper.

The magnitude of the induced polarization depends in a complicated way on the resistivity of the solution, on the amount and kind of clay, and on the particular cation saturating the clay. In general, when the concentration of the electrolyte is changed, the cation population is changed not only in the liquid but also in the clay. Unless the clay is saturated with the cation of the solution,

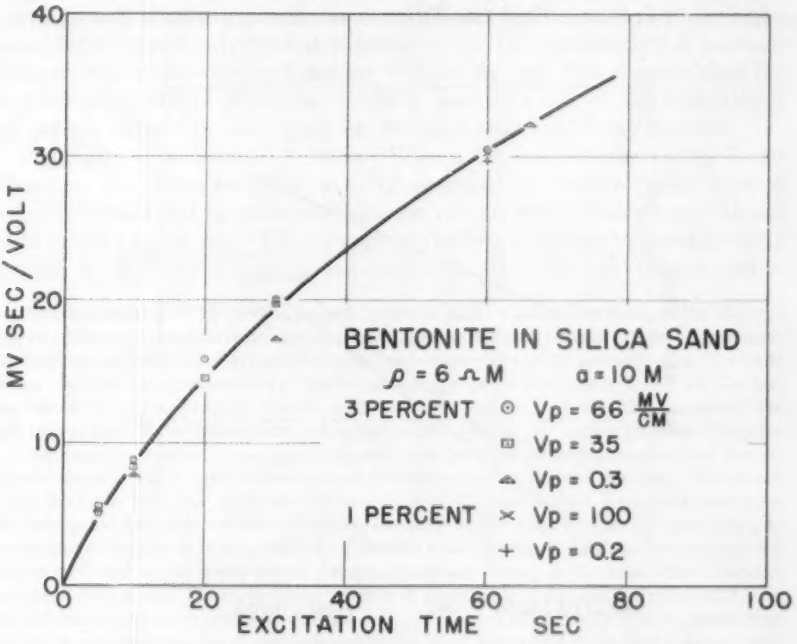

FIG. 3. Curve showing that induced polarization is independent of voltage gradient.

the induced polarization is not a single-valued function of the conductivity of the electrolyte, but slowly drifts to a constant value as the clay-electrolyte equilibrium is established. Generally the polarizability decreases with decrease in resistivity, so that clay banks and saline waters should give small effects.

The dependence of polarization on the amount of clay is complex; for amounts greater than three percent it depends on whether the clay is flocculated or dispersed. Saturation with sodium or potassium tends to make the clay swell, so as to fill up the pores of the matrix, which causes a drop of the polarization when too much clay is present. The same clay, when saturated with calcium, is flocculated into aggregates immersed in the electrolyte. These aggregates make a porous mass even without the addition of sand. With flocculated clays the polarizability increases with increasing clay content up to about from 5 to 9 percent of clay by dry weight. The significance of this experiment, in terms of natural conditions, is that the polarizability can be expected to increase with clay content corresponding to regions of finer sediments. As for compacted clay banks, experience indicates that their polarizability is small.

The chemistry of the water also changes the magnitude of the polarizability. The positive ions have the greatest influence, whereas the negative ions tried so far, namely chlorides, sulfates, phosphates, and carbonates, seem to have almost no effect on the polarizability. The carbonate solutions are difficult to work with,

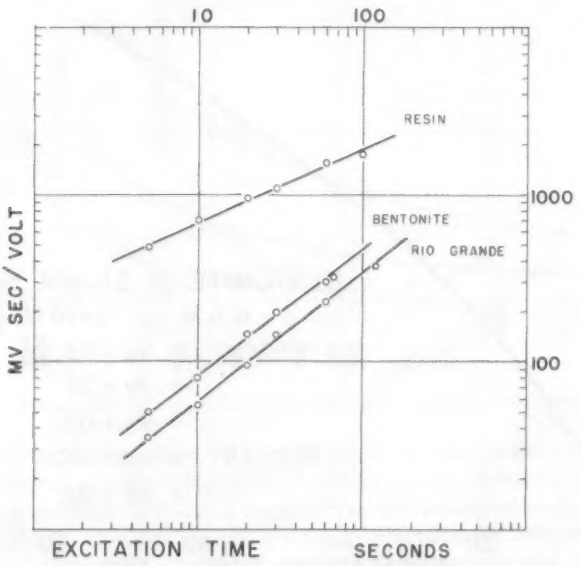

FIG. 4. Plots of induced polarization vs. time of excitation. The upper two lines are laboratory data for "Permutit" ion-exchange resin and a bentonite clay dispersed in sand. The lower line is taken from field observations in the Rio Grande Valley.

because they make complex ions. In studying the effect of the cation, the only safe procedure is to percolate the solution through the specimen until equilibrium is reached. One experiment consists of dividing a specimen of known composition between several holders and percolating a different solution through each holder. The other method is to percolate two solutions alternately through the same specimen. The latter can be used only when the clay behaves reversibly with alternate percolation. The polarizability of a certain montmorillonite used in some of our experiments increased by a factor of seven after slow percolation of a 100-ohm-meter solution of calcium chloride. In the natural condition of this clay, the exchange positions apparently were not occupied by calcium, which, in the case of this clay, gives a large polarization. Field measurements in the Tularosa Valley seem to corroborate this observation, the polarizability of the alluvium being fairly high despite the high salinity of the water.

Early in our study it was found that the polarizability of the sand-clay mixtures is roughly proportional to the ion-exchange capacity of the clay. Thus, montmorillonites are more active than kaolinites, and ion-exchange resins more active than montmorillonites. A clay saturated with hydrogen should, then, give no effect with an HCl electrolyte, because only one kind of cation, presumably, would be present. Fortunately, kaolinite from Dry Branch, Georgia, behaves reversibly with alternate percolation with HCl and NaCl. One of us performed a careful set of experiments which demonstrated that the polarizability of kaolinite is proportional to the amount of sodium held on the clay. This suggests that the electrical polarizability of the clay might be used as a tool by the mineralogist and the soil chemist to investigate ion-exchange reactions in clay minerals.

The purity of the kaolinite from Dry Branch, Georgia, was checked by X-ray diffraction. Its cation exchange capacity measured by Peech's (1945) method ranged between 6 and 14 milliequivalents per 100 gm. It then was electrodialyzed for 32 days at a slow rate.[1] The progress of the hydrogenation was measured by titration of the electrolyte in the end compartments of the cell. The electrodia-

[1] Electrodialysis is an electrolytic process by which positive metal ions fixed on the clay are stripped off and replaced mostly by hydrogen ions. The clay is placed into the central compartment of a three-compartment cell. Platinum electrodes are immersed in the end compartments. The walls between the three compartments are of special parchment paper, which is permeable to the ions but impermeable to the clay particles. The cell is filled with distilled water, so that the resistance of the cell is high at first. As the direct current strips the ions from the clay, the current increases. The process is monitored by titration of a sample of the electrolyte from the electrode compartments. Periodically the electrolyte in the end compartments is drained and replaced by distilled water. The current density has to be kept low, to prevent decomposition of the clay mineral. Even then, some clay gets decomposed and some metallic aluminum shows up at the cathode. The I.P. experiment in the field can be thought of as electrodialysis of the clay minerals in the ground. In that case, instead of being composed of parchment paper, the membranes are formed by the constrictions between clay-coated sand grains. The ion-sorting properties of plugs made of clay-contaminated sand have been studied in connection with self-potential well logs by McKelvey (1955). The statement that clay has an exchange capacity of 1 milliequivalent per 100 g means that it can fix 10^{-3} equivalents of a particular ion on 100 gm of clay. In the case of sodium, the atomic weight of which is 23, the amount fixed on 100 gm of clay would be 23 mg.

lyzed kaolin was dried, powdered, and mixed with 80- to 100-mesh silica sand (about 0.16 mm diameter) in the proportion of 5 percent kaolin to 95 percent sand by dry weight. The mixture was poured into a tubular glass sample holder of 2-cm i.d., with platinum current electrodes 24 cm apart and potential electrodes of silver coated with silver chloride 15.5 cm apart. Distilled water was introduced slowly into the tube from one end to the other. The specimen then was dried, in an attempt to coat the sand grains with clay. The tube was placed

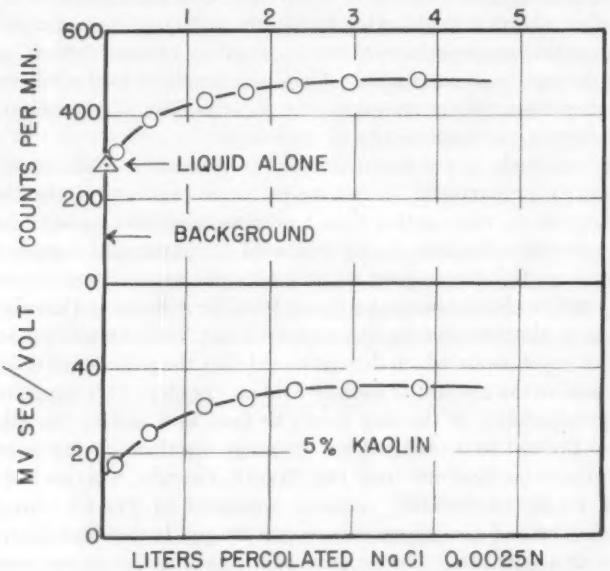

FIG. 5. Increase in induced polarization with increase of sodium content of a kaolinite specimen starting with the kaolinite saturated with hydrogen. The sodium is radioactively tagged with Na^{22}.

horizontally in a scintillation radiation counter (Nuclear Instrument and Chemical Corp., model DS_1) about 3 cm from the crystal and was not moved for the duration of the experiment, to preserve counting efficiency. Thus, radiation counting and induced-polarization measurements could be made simultaneously without disturbing the specimen. The sodium content of the specimen was determined quantitatively by mixing Na^{22}, which has a half life of 2.6 years, with the ordinary sodium in the proportion of 0.6×10^{-3} millicurie per milliequivalent of Na^{23}.

The upper curve of Figure 5 shows how the proportion of the radiation counts is determined for the liquid and for the clay. The tube containing the sample is first filled with all the liquid it can hold. The radiation count then represents the

amount of sodium in the electrolyte, as indicated in Figure 5 by the triangle. By slow percolation of 4 liters of 0.0025-N NaCl solution, the clay absorbs an additional amount of sodium until an equilibrium value is reached asymptotically. For low concentrations this equilibrium value is nearly a linear function of the concentration. Then, as the concentration becomes greater, the sodium content of the clay approaches its ion-exchange capacity. At saturation, for concentrations between 0.0007 N and 0.0025 N, the ratio of counts from liquid to counts from liquid plus clay is 49 percent.

To obtain the amount of sodium in milliequivalents from the counting rate, a known volume of given concentration of sodium solution just sufficient to saturate the specimen is introduced into the tube. It is assumed that the count is the same for a given amount of sodium whether in the liquid or on the clay. The departures of three determinations from the average were less than 1.5 percent, the average value being 2,650 counts per min per milliequivalent of sodium. From zero to 0.010-N concentration, the amount of sodium fixed on the clay as a function of the concentration xN can be expressed as

$$y = 0.5(1 - e^{-54x}) \text{ milliequivalents per 100 gm.}$$

The effect on the polarizability of alternate percolation with NaCl and HCl solutions of the same resistivities is shown by the set of curves at the bottom of Figure 6 for two values of resistivity of the solutions: 16 and 32 ohm-meters. The top pair of curves offer the corresponding data for the milliequivalents of sodium on the clay determined radiometrically. Although the sodium content of the clay drops to zero on percolation with HCl, the polarizability does not, but drops to a value one-third as large as it was for NaCl. A possible, but certainly not a necessary, cause for this residual might be the clogging of exchange positions with aluminum ions. According to Grim (1953, p. 142), "it is substantially impossible to prepare a clay in which all the exchange positions are occupied by H^+, since Al^{3+} moves from the lattice to exchange positions before saturation with H^+ becomes complete." It may be noted that in the case of this experiment, the polarizability is a linear function of the resistivity of the solution, even though, with the stronger solution, there is nearly twice as much sodium on the clay. Thus, in this case, the magnitude of the polarization increases with sodium content on the clay and decreases with ion concentration in the electrolyte. However, the sodium concentration in the electrolyte also increases the amount of sodium on the clay. The interplay of these two factors combines to produce an approximately linear variation of polarizability with the resistivity of the solution. This linear variation of polarizability with resistivity of sodium and potassium solutions has been observed for many samples containing kaolinite and montmorillonite. A general law, however, cannot be formulated, because equally valid experiments have shown that the rate at which the polarization increases with resistivity becomes less rapid as the solution becomes very dilute.

When the electrolyte contains two competing cations, the relative amounts of

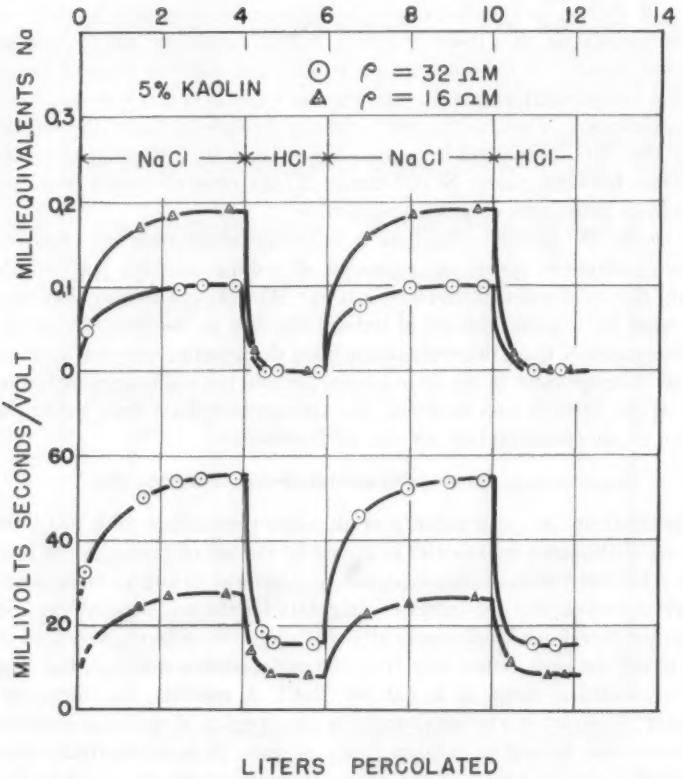

FIG. 6. Effect of alternate percolation of HCl and radioactively tagged NaCl for electrolytes of two resistivities. The residual I.P. for HCl solutions is ascribed tentatively to Al^{+++} occupying some of the ion-exchange positions.

these ions fixed on the clay depend in general not only on their relative concentrations in the electrolyte but also on the relative affinities of the clay for these ions. This, again, has been shown for the 5-percent kaolinite samples percolated to equilibrium with solutions of the same resistivity (32 ohm-meters), consisting of mixtures of radioactively tagged NaCl and 0-, 2-, 5-, 10-, 25-, 50-, and 100-percent HCl. In Figure 7 the percentage of sodium held by the clay and the polarizability are plotted against the percentage of sodium in the electrolyte. The character of the two curves is the same, except that there is a residual polarizability for zero sodium content. The data show the well-known fact that the affinity of kaolin for hydrogen is greater than for sodium.

The rate of polarization decay is independent of the concentration of the

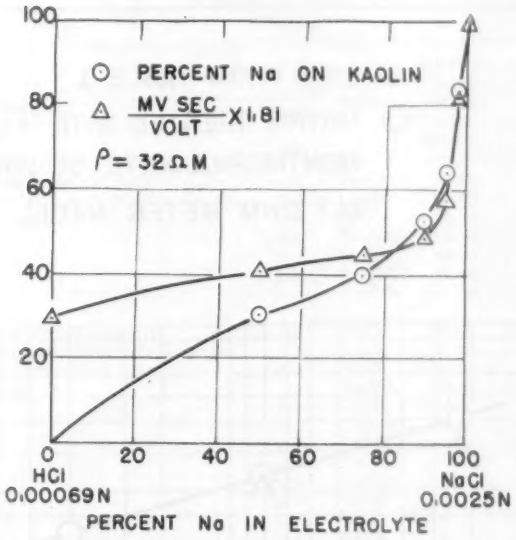

FIG. 7. Effect on induced polarization of relative affinity of kaolinite for protons and for sodium atoms. Ten percent of H^+ reduces the I.P. by 50 percent.

electrolyte and does not seem to be affected greatly by the kind of clay and the chemistry of the water. The rate of decay seems to be influenced principally by the grain size of the sand. Since the decay is not exponential but fits a hyperbolic expression

$$\text{I.P.} = \frac{K}{(C + t)^x},$$

by proper choice of the constants C and K, I.P. can be plotted against the time t as a straight line on log-log paper. The slope of the line is x and is a measure of the rate of decay. Instead of this cumbersome procedure, we take the ratio of ordinate at 5 sec to that at 20 sec. The smaller this ratio, the longer is the relaxation time, and the coarser the alluvium. The practical importance of this property cannot be overemphasized, as it might open the possibility of locating permeable areas in silted-up valleys. Figure 8 shows an experimental determination of this variation. The ratio of the 5-sec to the 20-sec ordinate for 3-mm glass beads coated with montmorillonite is less than half the value for the 80- to 100-mesh sand. The third column of Table I lists the individual values obtained for the ratio of the 5-sec to the 20-sec values of polarization for fine and coarse sand for various electrolytes and conditions of the clay. Whether the departures from the averages are meaningful is questionable. For example, electrodialyzed kaolin in fine sand with $AlCl_3$ solution has a longer relaxation time, indicated by the ratio

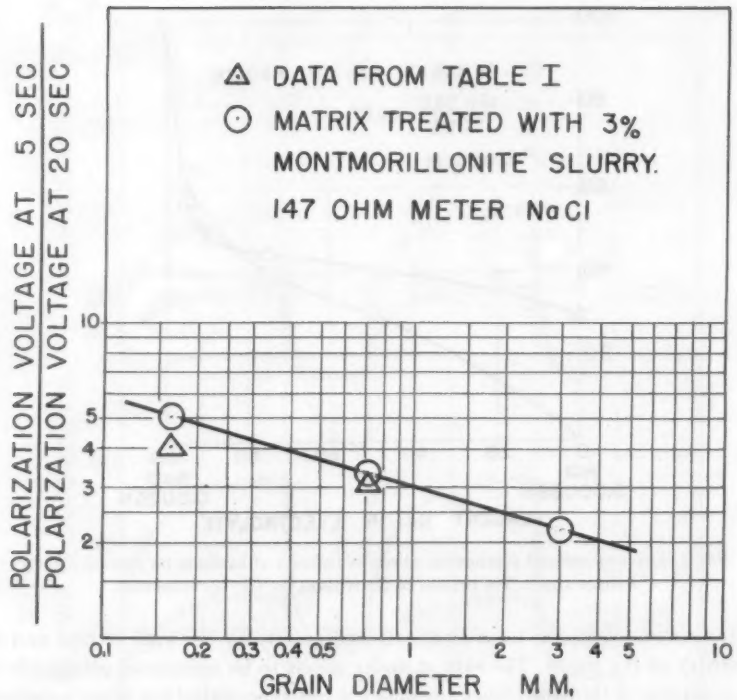

FIG. 8. Effect of grain diameter of the sand on the rate of decay of induced polarization.

2.9, than the natural montmorillonite in coarse sand with the same solution, which gives a ratio of 3.0. Fine and coarse arroyo sand, the last item of the table, showed a large difference in 5:20-sec ratios. The clay mineral in the arroyo sand consisted of montmorillonite, with a trace of pyrophyllite. The average values of the 20- to 30-mesh and 80- to 100-mesh sands, omitting two discordant values for kaolin with $AlCl_3$, are plotted as triangles in Figure 8.[2]

Table I gives a portion of the data taken last summer in open-trough sample holders. Those samples were selected for which the 5:20-sec I.P. ratio was tabulated in the data book. The 45 samples selected according to this arbitrary criterion illustrate most of the points made in the foregoing discussion.

The clays were a montmorillonite from a perlite mine, having an ion-exchange capacity of 89 milliequivalents per 100 grams, and the kaolinite from Dry Branch, Georgia, which had an ion-exchange capacity of 10 milliequivalents per 100 g. The clay could be in three conditions, its natural state, electrodialyzed, or

[2] The average particle diameters for these two grades of sand are 0.16 mm and 0.72 mm respectively.

TABLE I

LABORATORY INDUCED-POLARIZATION MEASUREMENTS IN OPEN TROUGHS

All specimens 100 g
Time of excitation: 20 sec

Material	Sand Mesh	5:20-sec Ratio	Solution	Resistivity of Solution (Ohm-Meters)	5-sec I.P. (mv/v)	Item
2.5% montmorillonite, natural state. Sample saturated with 27 cc of solution; not percolated	20–30	3.5	NaCl	17.00	3.39	1
		3.4	$CaCl_2$	16.65	2.70	2
		3.0	$AlCl_3$	16.45	2.56	3
		3.4	Na_2SO_4	17.50	3.35	4
		3.3	$CaSO_4$	20.50	2.90	5
		3.1	$Al_2(SO_4)_3$	26.10	2.90	6
		3.3	Na_3PO_4	16.80	7.86	7
2% montmorillonite saturated by 0.1 N solutions, then washed with distilled water and percolated with indicated solution	20–30	—	NaCl	80.0	Dispersed	8
		3.5	$CaCl_2$	80.0	18.0	9
		2.4	$AlCl_3$	80.0	8.3	10
		—	Na_2SO_4	80.0	Dispersed	11
		2.9	$CaSO_4$	80.0	20.2	12
		2.4	$Al_2(SO_4)_3$	80.0	10.0	13
		3.3	$CaSO_4$	340	32.7	14
		3.2	$CaSO_4$	78	22.0	15
		3.2	$CaSO_4$	19	10.5	16
		3.2	$CaSO_4$	6.3	4.7	17
		2.9	K_2SO_4	78	4.7	18
		3.1	K_2SO_4	16	4.5	19
Same, except saturated first with 0.2 N solution	20–30	2.7	$CaSO_4$	270	25.9	20
		2.7	$CaSO_4$	71	11.5	21
		3.0	$CaSO_4$	18	3.43	22
		3.1	$CaSO_4$	6	1.09	23
Average	20–30	3.08				
2.5% electrodialyzed montmorillonite. Saturated with 27 cc of solution; not percolated	80–100	3.8	NaCl	17.0	3.48	24
		4.5	$CaCl_2$	16.6	2.94	25
		4.4	$AlCl_3$	16.3	2.75	26
		4.0	Na_2SO_4	16	4.27	27
		3.9	$CaSO_4$	19	3.40	28
		3.8	$Al_2(SO_4)_3$	—	3.58	29
1% electrodialyzed montmorillonite. Saturated with 27 cc of solution; not percolated	80–100	3.6	$CaSO_4$	300	6.70	30
		4.0	$CaSO_4$	69	5.56	31
		4.0	$CaSO_4$	17	3.93	32
		3.7	$CaSO_4$	5.7	2.28	33
		4.0	K_2SO_4	14.5	3.62	34
		4.0	K_2SO_4	65.5	5.82	35
5% montmorillonite—5% kaolin; not percolated	80–100	3.3	$CaSO_4$	30	Not recorded	36
	80–100	5.0	$CaSO_4$	30		37
5% kaolin; electrodialyzed and percolated	80–100	(2.9)	$AlCl_3$	70	1.75	38
		3.5	$CaCl_2$	77	2.06	39
		3.5	NaCl	81	2.12	40
5% kaolin; ion-saturated and percolated	80–100	(2.7)	$AlCl_3$	70	1.19	41
		5.2	$CaCl_2$	77	4.06	42
		4.2	NaCl	81	1.55	43
Average	80–100	4.02				
Arroyo sand	10–40	2.4	NaCl			44
Arroyo sand; finer than 40 mesh		3.96	NaCl			45

ion-saturated by treatment with a concentrated solution of the ion under investigation.

The sand and the clay were mixed when dry by tumbling, and a set of troughs were filled with 100 gm specimens from the same batch. In one type of experiment each trough was saturated with 27 cc of a particular solution. For example, if the influence of different positive ions was being determined, a set of troughs would be prepared, each saturated with a different solution. In the other type of experiment several liters of a given solution were percolated through the specimen, sometimes for several days. Except for the preparation of the ion-saturated specimens, each trough received only one solution. To prepare the ion-saturated specimens, a great excess of a strong solution, usually 0.1 to 0.2 N, was percolated through the specimen for over a day. It was then flushed with distilled water, followed by a liter or more of the particular solution for which the induced-polarization value was sought.

Except for the sodium phosphate, the 5-sec I.P. values are very much alike for items 1–7 of Table I. The same can be said of items 24–35 for 2.5-percent and 1.0-percent electrodialyzed montmorillonite. Items 28 and 32 make it appear as though the effect were not sensitive to the amount of clay. Actually this is not so; the amounts of solution in the two cases were the same, whereas the amounts of clay were not, so that ionic concentrations on the clay and in the liquid are different in the two cases. When the solution is percolated, as in item 16, the 5-sec I.P. value is 10.5 millivolts per volt for the same concentration, whereas when it is not percolated, it is only 2.9, as in item 5.

The precision with which the readings can be repeated is exemplified by specimens 12, 9, and 15, which give 18.0, 20.2, and 22.0 millivolts per volt for three different specimens percolated with the same concentration of calcium salts.

Items 14–17 show the variation of I.P. with a hundredfold range of concentration of the electrolyte. The potency of the calcium ion in this particular clay is shown by comparing the 5-sec I.P. for item 15, which is 20.0 millivolts per volt, with the value of 4.7 millivolts per volt (item 18), the value for the potassium ion for the same concentration. Calcium is also more potent than sodium or aluminum in the case of kaolin, as can be seen by comparing items 38–43. However, the difference is brought out only after soaking the clay in concentrated solutions. These data indicate also that the valence of the cation has little to do with the polarization phenomenon.

The general picture that emerges is that induced polarization is a result of local electrodialysis of the clay across semipermeable partitions formed by adjacent sand grains. In Figure 9 the gradient of the electric field shown by the arrow is steepened in the constriction formed by adjacent sand grains, so the current density in the conducting path formed by the clay is greater than in the regions adjoining the cavities between the sand grains. The conduction over the clay in these constricted regions affects the concentration of the exchangeable cation of the double layer. It is necessary to pass the current for several minutes before

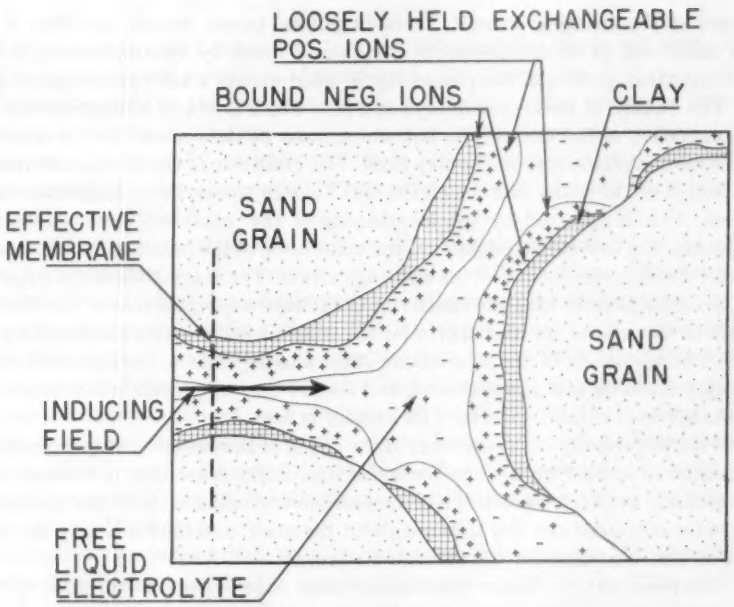

FIG. 9. Configuration of electric charges in pore of aquifer.

equilibrium is reached against disordering forces. When the current is shut off, the exchangeable ions slowly redistribute themselves along the clay. It is interesting to note that the rate of decay is independent of the concentration of the electrolyte. For the concentrations used, the cationic population of the liquid is negligible compared with that on the clay. However, the absolute magnitude of the polarization does depend on the resistivity of the liquid. We propose tentatively that the function of the clay during the relaxation phenomenon is to provide a source and a sink of ions, the rate of such provision being nearly independent of the ion concentration in the liquid. For dilute solutions, the voltage across each membrane is proportional, however, to the ratio of the logarithms of the concentrations, according to Nernst's equation:

$$E = \frac{RT}{nF} \log_e \frac{c_1}{c_2},$$

where R is the universal gas constant, T the absolute temperature, n the valence of the ion, F the Faraday constant, and c_1 and c_2 the two concentrations. This ratio becomes smaller if the liquid contains a great many cations already, instead of just a few. The effect will increase also if the clay is saturated already with cations, because more ions will move in and out of the clay under the in-

fluence of the charging current. In more general terms, we can say that if the clay subjected to electrodialysis *in situ* cannot move by electrophoresis, it sets up concentration cells in the porous liquid-filled matrix when the current is shut off. The voltage of these cells decays at a rate which is nearly independent of the concentration of the electrolyte, but which must be determined by the mobility of the exchangeable ions on the clay itself. The grain size of the matrix determines the length of the paths over which the ions have to travel, being longer for larger grains. This is reflected by the lengthening of the relaxation time with larger grain size. For low-current densities, the magnitude of the polarizability is exactly proportional to the density of the exciting current. The magnitude of the polarizability varies directly with the resistivity of the electrolyte, because of the diluting effect of the ions of the electrolyte on the concentration ratios produced by the clay. The amplitude of the polarization effect also depends on the ease with which the clay takes on and gives off ions, and should thus be greater when the clay is saturated with cations for which its affinity is low.

A subject worthy of future study is the origin of the background polarizability encountered in field work when the soil is dry, in the sense that it does not hold interstitial, available water. Field measurements indicate that the relaxation times for saturated and dry soils are about the same, and that it is only the magnitude that is greater for the saturated alluvium.

The preceding discussion emphasizes those experiments which directly contribute to our present conception of the general mechanism of induced polarization. Dakhnov and others (1952), in their work on induced polarization as applied to well logging, ascribe induced polarization to electroendosmosis and streaming potentials. Before we were aware of their work, we found that electroendosmosis and streaming potentials, although undoubtedly present, are much too small to account for the magnitude of the observed polarization effects. Furthermore, the streaming potentials for clean sand and sand with one percent bentonite are very nearly the same, whereas their induced polarization differs by a factor of 20. In discussions with electrochemists, much time was spent in assessing the influence of electrode potentials. In retrospect, not all our laboratory experiments were impeccable in this respect; electrode potentials occasionally produced some confusing results. Suffice it to say that the field measurements and the measurements obtained from the model laboratory tank, to be discussed later, cannot be explained by electrochemical effects at the potential electrodes, or by macroscopic changes in ion concentrations at the current electrodes.

Further evidence that polarizability depends on ion exchange rather than on just the presence of hydrophilic colloids in the ground was obtained by cementing sand with ferric hydroxide by precipitation from ferric chloride with ammonia. After washing with distilled water, the mixture exhibited no polarization. It was roasted then to transform the limonite to hematite, another colloidal cement that occurs in nature. The artificial red sandstone thus produced was likewise electrically inert.

FIELD SURVEYS

Laboratory studies have shown that the polarizability measured in the field may be due to several properties of the ground. The interpretation of the surveys, therefore, depends on the particular geologic situation which has to be inferred from other sources of information. Two special assumptions can be made: One postulates a horizontally layered earth, as is done in resistivity prospecting; the other postulates a lateral variation of properties, such as a buried water-bearing channel in an alluvial fan.

In resistivity prospecting, contrasts are often absent or unrelated to the water table. Induced polarization, however, can supply contrasts where there are none in resistivity and which specifically pertain to content of available water. In the companion article by Frische and von Buttlar (1957), a method is developed for computing depth to water from polarization data on the basis of a horizontally stratified earth. Effects from lateral variations of polarizability are not amenable to quantitative calculations, and one must be satisfied with "indications" read on the map, supplemented by experiments on laboratory models. Nevertheless, it is often important to intercept the water in alluvial fans close to the highlands before it becomes charged with chlorides and sulfates, which occur as a rule in the river valleys of arid lands.

In the field the same principles of operation are followed as in the laboratory. Current from generator G (Fig. 10) is interrupted after passing through the ground for a fixed time, usually 30 sec. A few milliseconds later the measuring device is connected to the nonpolarizing potential electrodes, and the area under the decay curve, in millivolt seconds, is determined. This area, when divided by the voltage between the potential electrodes during the passage of the current, gives the polarizability. This polarizability, expressed in millivolt seconds per volt, or milliseconds, is plotted against the electrode separation a of the Wenner electrode configuration. The Wenner configuration is shown at the upper left of Figure 10. The generator used in field surveys furnishes a charging current of 3 or 4 amp at about 850 v.

The generator is a permanent-magnet 800-cps alternator with semiconductor rectifiers, developed by the Georator Corp., of Manassas, Virginia. At present it furnishes about 9 kw at either 600 or 1,200 v. It is driven by a power takeoff from the engine of the truck. For the longer electrode spacings, current is introduced into the ground through clusters of steel stakes watered with brine. The wire reels are power driven from the truck's electrical system and hold enough wire for a Wenner spacing a of 1,000 ft. It is very seldom, however, that a's in excess of 640 feet have been used, because of the drop in signal strength with increasing electrode separation. The drift of the copper-copper sulfate potential electrodes and natural earth-current potentials determine the noise level in the measuring circuit. For the larger electrode separations, the peak of the decay curve is only about one millivolt, so that during most of the period of integration, which is usually two minutes, the signal is less than 0.1 millivolt. Although our field ob-

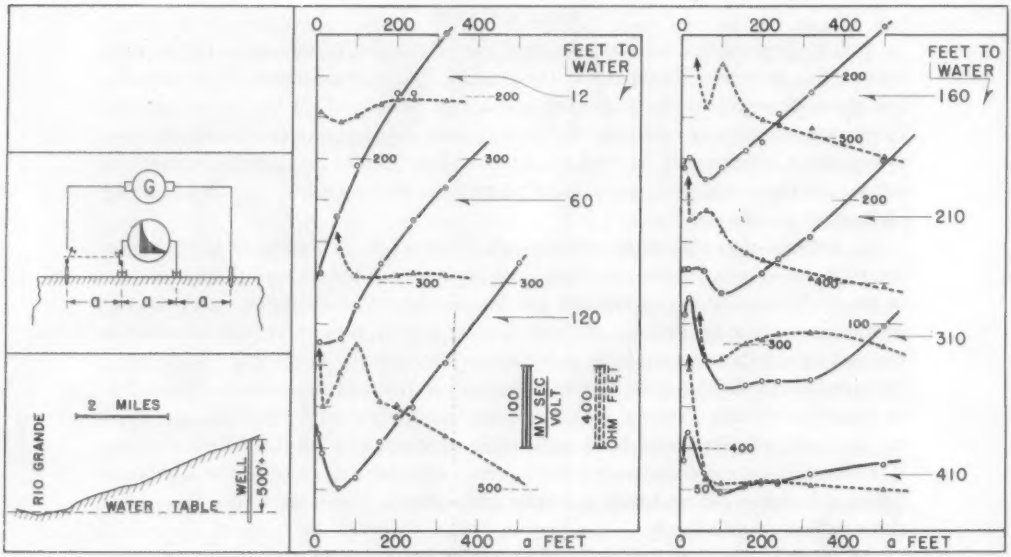

FIG. 10. Induced polarization and apparent resistivity vs. Wenner electrode spacing a for different depths to the water table in the Rio Grande Valley near Socorro, New Mexico.

servations were taken with a specially constructed amplifier and integrator, it is recommended that a Kay Lab microvoltmeter, model 202, followed by an appropriate connection to a recorder, as previously described, be used for measurements of this type. At the time of this writing (November 1956), an experimental equipment using square-topped pulses with a repetition frequency of 7 cps is being installed by the Houston Technical Laboratories, Houston, Texas, for trial in the field truck. It is hoped that this ac equipment will increase the sensitivity and speed up the field operation by cancelling the earth-current disturbances and potential-electrode drift.

Figure 10 shows a profile which was observed across the Rio Grande Valley from the river to a well 500 ft deep. The origin of the polarization curves plotted against the Wenner electrode separation a, in feet, was shifted downward for each curve; thus, the curves are spread out. The steepness of the positive slopes is indicative of water. At a depth of 310 ft it is still detectable, but indication is lost when the water table is 410 ft down.

The apparent resistivity in ohm-feet is plotted in Figure 10 as the dashed curves. For values of a greater than 200 ft, the polarization and resistivity curves have opposite slopes, as one would expect for a two-layer earth in which the top layer is dry (i.e., highly resistive and unpolarizable), whereas the lower material, being wet, is lower in resistivity and high in polarizability. The sharp peaks for

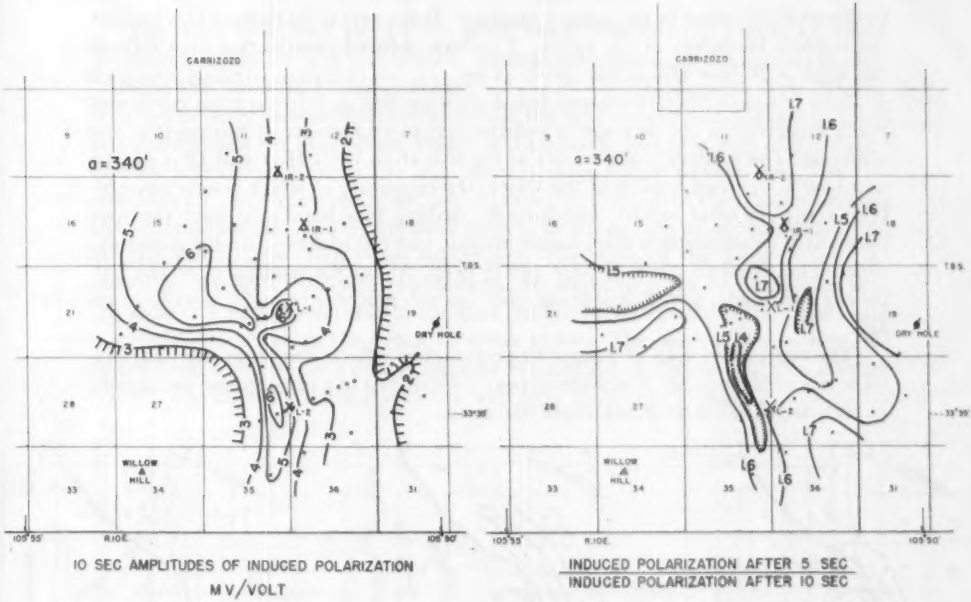

FIG. 11. I.P. survey near Carrizozo, New Mexico. Left map shows contours of I.P. magnitude in mv/volt 10 sec after current is shut off. Right map shows the ratio of the amplitudes at 5 and 10 sec, presumably reflecting pore size of aquifer. A well producing over 100 gal/min was brought in at recommended location L-1.

very low values of a in some of the curves are caused by accumulation of rainwater that never reaches the water table. The polarization values for Wenner electrode spacing a of 40 ft and less show marked seasonal variations. For the greater values of a, the polarization is seasonally invariant.

The maps of Figure 11 are more difficult to interpret. A small valley about 15 square miles in area, just south of the village of Carrizozo, New Mexico, lies at the foot of the Sierra Blanca, which rises more than 4,000 ft above the valley only 4 miles to the southeast. These highlands are volcanic and produce good water. Unfortunately, near the mouth of the valley, to the north and west, the Cretaceous sediments of the great Tularosa Valley charge the water with chlorides and gypsum. Here one has to intercept the water while it is still in volcanic alluvium, or not too far away from it, by locating buried channels, much as the Persians did near Teheran 200 years ago. The existence of such buried channels is indicated by the irrigation well labeled IR-1 in Figure 11. This well is being pumped at the rate of 1,000 gal/min, enough to irrigate a section of land.

The map on the left-hand half of Figure 11 gives the induced polarization in millivolts per volt for an electrode spacing of 340 ft, 10 sec after the energizing current is shut off. The contours seem to indicate that the subsurface drainage

conforms in direction to the surface drainage. It appears to be dammed up against the western boundary of the valley. A narrow induced-polarization high follows the edge of Willow Hill as far south as sec. 35. On this basis, drilling locations L-1 and L-2 have been recommended. Following this high toward the north and west, we attribute the increase in polarization to an increase of thickness of the alluvium. The relatively low values at the irrigation wells IR-1 and IR-2 can be ascribed to the poor quality of the water, the resistivity of which is only 20 ohm-ft (1,190 ppm total solids). Incidentally, drilling location L-2 is near the spot previously recommended from earlier seismic and electrical-resistivity investigations. The alluvium there is only 130 ft deep. About six months after the I.P. survey was made, a well producing over 100 gal/min was brought in at location L-1.

The right-hand map of Figure 11 presumably reflects the grain size or transmissivity of the aquifer. The wells appear to be drilled in a fine-grained formation; in fact, well IR-1 does pump some fine sand.

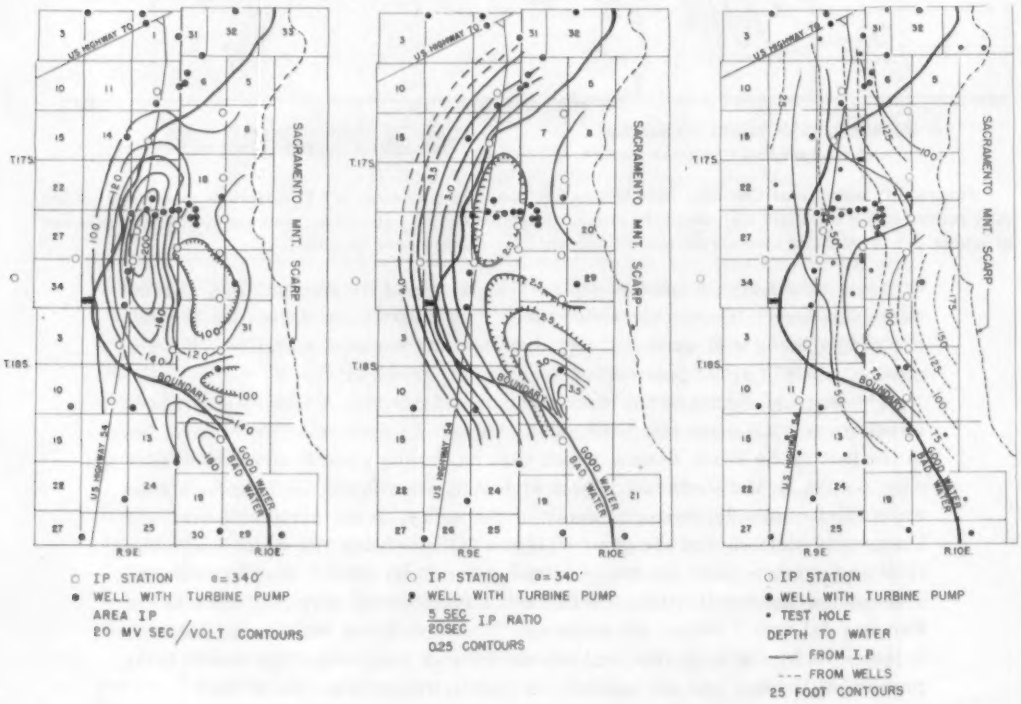

FIG. 12. I.P. survey south of Alamogordo, New Mexico. Left map shows I.P. high over known accumulation of good water. Middle map shows that productive well farm is characterized by greater permeability. Right map gives depth to water from wells, computed from I.P. measured with expanding electrode spreads.

The effect of salinity and aquifer grain size is illustrated in Figure 12, which shows an I.P. survey of a well-known, remarkable occurrence of excellent quality water in the Tularosa Valley, just south of the city of Alamogordo, New Mexico. A group of wells clustered in the middle of the map supply about 1,000 gal/min to the Holloman Air Force Base. Water in the surrounding area west of the water-quality boundary indicated on the maps is unfit for household use. The tremendous I.P. high centered in sec. 26, T. 17 S., R. 9 E., gives the impression that the water issues from an underground spring. This is not the accepted explanation for this remarkable fresh-water occurrence. The ratio of the 5- to 20-sec I.P. shown on the middle map corresponds to the producing area and indicates that the aquifer is more permeable in the zone producing fresh water. The right hand map of Figure 12 gives the depth to water in feet. The solid contours were obtained from computations on I.P. data by the method of Frische and von Buttlar (1957). The dotted contours are from well data by Meeks (1950).

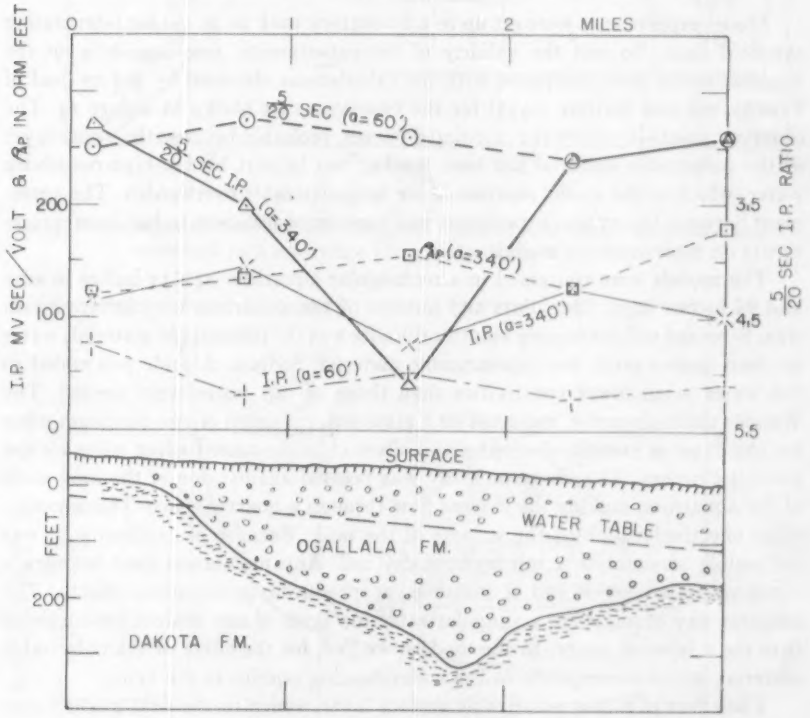

FIG. 13. I.P. survey south of Clayton, New Mexico. The buried valley shows up in the 5/20 sec I.P. ratio. The water table at about 100-ft depth is indicated by larger I.P. for $a = 340$ ft, as compared with the I.P. values for $a = 60$ ft.

Through the courtesy of the Continental Oil Co., data were obtained from closely spaced shotholes south of Clayton, New Mexico, which outlined a buried valley in the Dakota formation (Fig. 13). The water table lies about 100 ft below the ground surface mostly in the Ogallala formation. I.P. was measured at five stations along the profile with Wenner electrode spacings of 60 and 340 ft. For the short spacing, the I.P. fluctuates about an average value of 50 millivolt seconds per volt, whereas for the long spacing, it averages about 110, reflecting the presence of the water table. The 5- to 20-sec I.P. ratio for the long spacing clearly indicates the buried valley. The apparent resistivity curve for the same spacing is quite featureless. Although the data are too scant for drawing definite conclusions, the numerical values of the 5- to 20-sec ratio are obtained by averaging six or more individual measurements, so that the high value of five for the station in the middle of the graph is well established.

MODEL EXPERIMENTS

Model experiments were set up in a laboratory tank as an aid for interpreting the field data. To test the validity of the experiments, measurements on the simplest model were compared with the calculations obtained by the method of Frische and von Buttlar (1957) for the two-layer case shown in Figure 14. The observed points lie above the calculated curves, probably because the upper layer of the polarizable material has been leached out in part by the high-resistivity water, which in the model represents the nonpolarizable overburden. The agreement between theory and experiment was considered sufficient to justify measurements on more complex models.

The models were contained in a rectangular aquarium 24×12 inches in area and 14 inches high. The joints and bottom of the aquarium were covered with wax. Screened soil containing montmorillonite was the polarizable material; water or clean quartz sand, the unpolarizable material. Sodium chloride was added to the water when lower resistivities than those of tap water were needed. The Wenner electrode array, mounted on a glass rod, consisted of two platinum wires for the outer or current electrodes and silver chloride-coated silver wires for the potential probes. The electrode array was pressed against one of the long walls of the aquarium, making the current flow through a quarter space. This arrangement effectively doubled the volume of the tank. Because of capillarity, it was impossible to simulate a top layer of dry soil. Any membrane used between a water-saturated layer and a moist layer produced polarization effects. The simplest way of modeling a nonpolarizable top layer of any desired conductivity is to use a layer of water. In the models, we look for the effect of the polarizable material, which corresponds to the water-bearing aquifer in the field.

The effect of a thin polarizable surface layer, which in the field might correspond to surficial moisture due to rain, is shown in Figure 15. This curve can be combined with the curves of Figure 14 to give in a qualitative way the appearance of field curves common in arid lands, where the moisture due to rainfall is separated from the water table by a dry layer. Some of the field curves of Figure

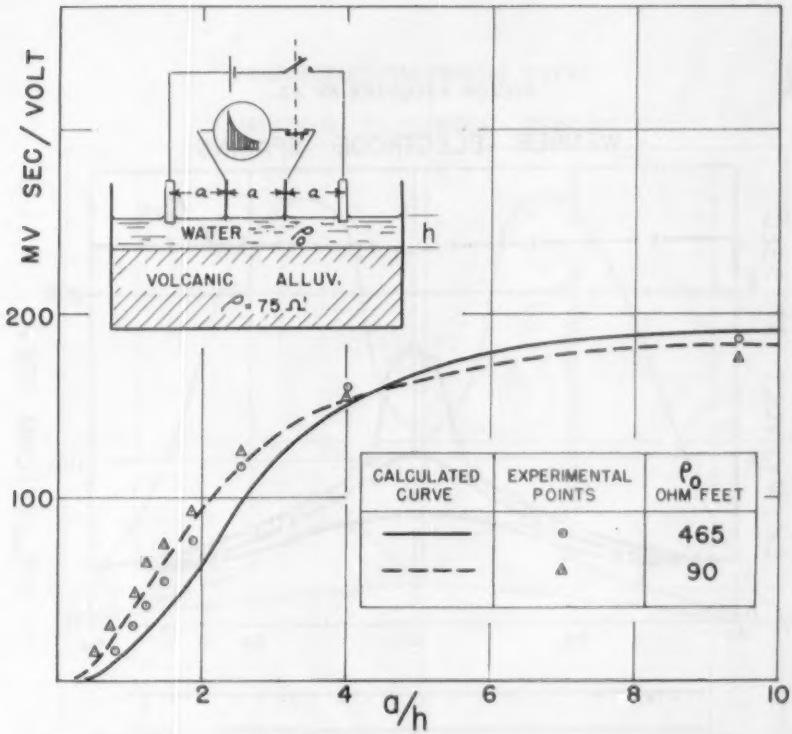

FIG. 14. A comparison of theoretical I.P. curves with experimental points obtained in a laboratory-model tank for a 2-layer case where the bottom layer is polarizable.

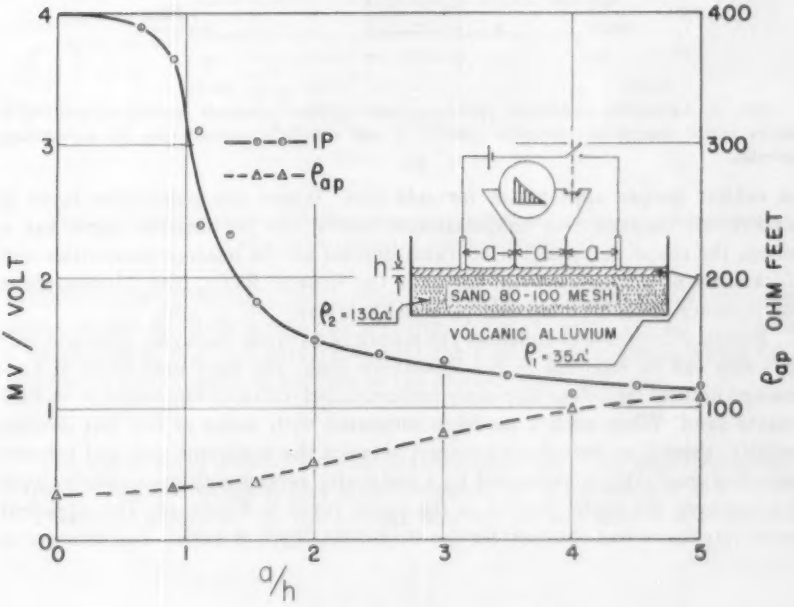

FIG. 15. I.P. and apparent resistivity curves obtained in laboratory-model tank for a 2-layer case where the top layer is polarizable.

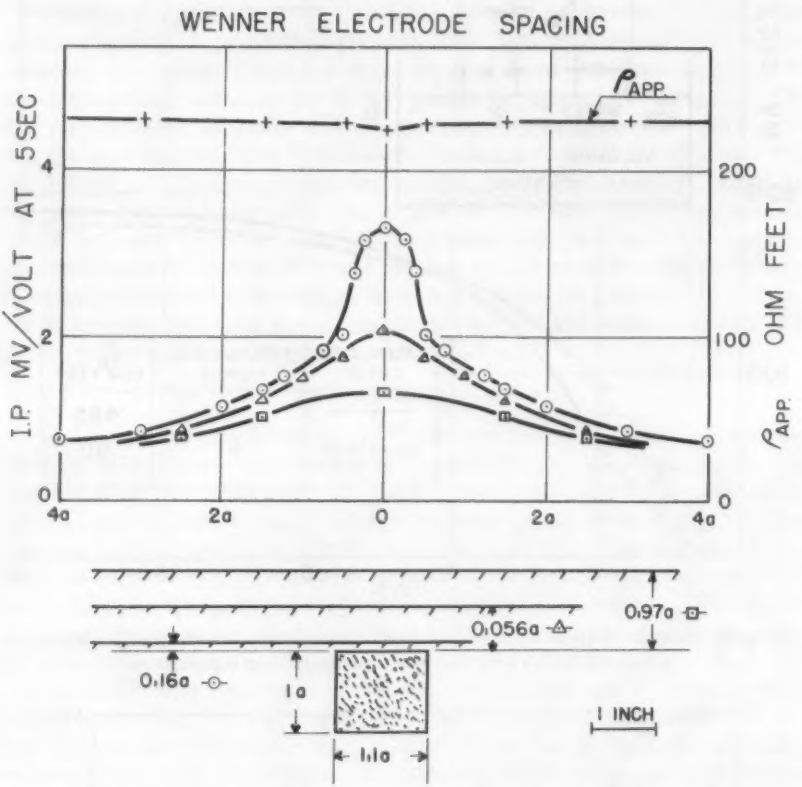

FIG. 16. Laboratory-model-tank experiment with constant electrode spacing representing a narrow buried channel of polarizable material of zero resistivity contrast with the surrounding material.

10 exhibit shapes appropriate for this case. Where the polarizable layer is sandwiched between two nonpolarizable layers, the polarization curve has a hump, the shape and position of which depend on the relative resistivities and thicknesses of the layers. Field curves in the Roswell Basin, New Mexico, show the presence of such buried thin polarizable layers.

Buried polarizable channels at the mouth of canyons emptying into arid valleys also can be modeled in the laboratory tank. We have used slabs of fine-grained natural sandstone obviously contaminated with clay embedded in washed quartz sand. When such a model is saturated with water of low but definite salinity, there is no resistivity contrast between the sandstone slab and the surrounding sand; this is evidenced by a resistivity survey with constant electrode spacing over the model plotted as the upper curve in Figure 16. This apparent resistivity curve was obtained for the shallowest depth of burial. The presence of

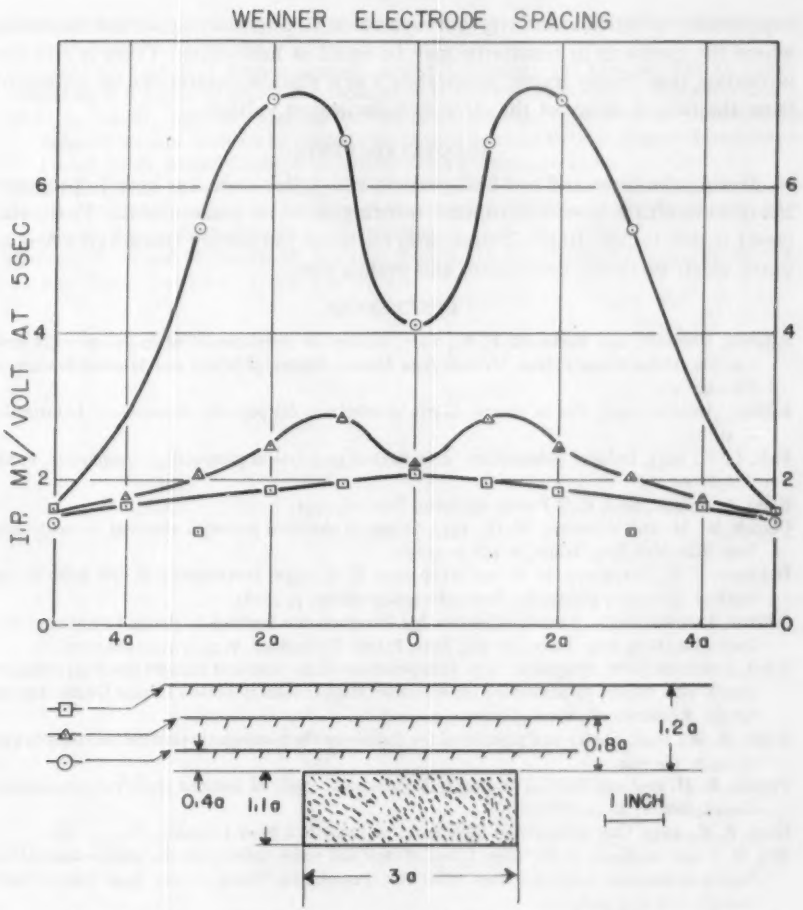

FIG. 17. Laboratory-model-tank experiment with constant electrode spacing representing a wide buried channel of polarizable material.

the polarizable sandstone is clearly shown, however, on the I.P. profiles measured with constant electrode spacing for all three depths of burial. The I.P. curves for a wider slab, shown in Figure 17, exhibit the characteristic double hump for a polarizable body, except in the case of the deepest depth of burial.

CONCLUSION

The usefulness of induced-polarization measurements in the search for ground water will become apparent only after continued use of the method in a variety of hydrologic situations. At the present time we can say that it is a valuable

supplement to earth-resistivity surveys since it provides significant contrasts where the contrasts in resistivity may be small or misleading. There is also the indication that the hydraulic permeability of a shallow aquifer can be estimated from the rate of decay of the induced-polarization voltage.

ACKNOWLEDGMENTS

During the three and one-half years in which this work has been in progress, many individuals have contributed to bring it to its present state. Particular credit is due to Mr. Roger Torres, who outfitted the survey truck and acted as party chief, surveyor, draftsman, and permit man.

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GEOPHYSICS, VOL. XXII, NO. 3 (JULY, 1957), PP. 688-706, 9 FIGS

A THEORETICAL STUDY OF INDUCED ELECTRICAL POLARIZATION*

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ABSTRACT

A mathematical solution is obtained and numerically evaluated for determining the depth to a saturated aquifer when prospecting for ground water by induced electrical polarization. In a horizontally stratified earth model consisting of a nonpolarizable overburden and an underlying, infinitely deep polarizable layer, the induced-polarization potential difference for a Wenner electrode configuration is nearly independent of the resistivity contrast. The computation agrees with results from a laboratory model tank and with a field curve. This justifies confidence in the validity of the results obtained from the model tank on earth models too complex for computation.

INTRODUCTION

When an aquifer contaminated with clay minerals and saturated with water is made to conduct direct current, it can become electrically polarized as though consisting of a mass of little electrolytic cells. Dry earth materials do not exhibit this effect. At the New Mexico Institute of Mining and Technology, field experiments have been underway for three and a half years to determine whether this electrical polarization of clay-contaminated aquifers can be used for locating new supplies of ground water. In this paper a mathematical expression for the polarization effect is derived and numerically evaluated for a simple earth model, in order to guide experimental model studies in the laboratory and assist in interpreting field measurements.

The field procedure consists of sending a direct current I (measured at A) through electrodes 1 and 2, as shown in Figure 1, for a given length of time, then interrupting the current, and recording the voltage between electrodes 3 and 4. Usually the ground is energized for 30 seconds, and the decay of the relaxation voltage is observed for two minutes. The value of the relaxation voltage immediately after the current is shut off is designated by $\Delta\phi$; in the field, its value is of the order of 10 millivolts, whereas when the current is flowing, the voltage V between electrodes 3 and 4 is of the order of one volt. It has been demonstrated that the ratio $\Delta\phi/V$ is independent of the value of V (Vacquier et al., 1957); therefore, this ratio represents a specific property of the aquifer. Since $\Delta\phi$ is two orders of magnitude smaller than V, its detection is difficult by alternating-current methods. Because the relaxation voltage persists, taking 15 seconds to drop to half value, it is observed easily after the current is shut off. The time dependence of this decay is the same for all portions of the uniform aquifer. The

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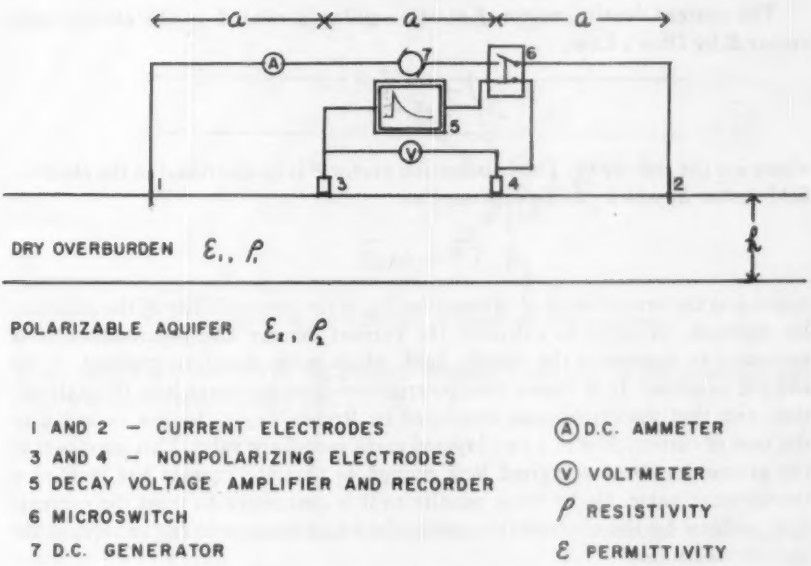

FIG. 1. Simplified diagram of Wenner electrode configuration and circuit used in field apparatus.

present study does not consider the physicochemical mechanism by which the ground acquires polarization or the various factors which influence its decay. The study is restricted entirely to the determination of $\Delta\phi/V$ as a function of the Wenner electrode spacing a for the case of a horizontally stratified earth model. The values of the polarization potential for two values of the electrode spacing a will bear the same ratio to each other for any chosen time interval measured from the instant the energizing current is broken. This ratio is also independent of the length of time the ground is energized. Thus, time does not appear in the equations.

The earth model that was used is shown in Figure 1. It consists of a dry overburden of uniform thickness h, possessing an electric permittivity[1] ϵ_1 and a resistivity ρ_1, and of a saturated aquifer of electric permittivity ϵ_2 and resistivity ρ_2, extending to infinity below this depth h. Curves have been computed for $\Delta\phi$ as a function of the electrode spacing a for various ratios of ρ_1 to ρ_2. It is assumed that only the lower layer is polarizable, the permittivity of the air and of the upper layer always being that of vacuum. The electrical behavior of the aquifer is assumed to be completely defined by its resistivity and dielectric constant, even though the aquifer is certainly not a dielectric in the conventional sense.

[1] The electrical quantities and formulae used in this paper are defined in meter-kilogram-second-ampere units.

The current-density vector J in the aquifer is related to the electric-field vector E by Ohm's Law:

$$\vec{J} = \frac{\vec{E}}{\rho},$$

where ρ is the resistivity. The polarization vector P is proportional to the electric-field vector E, which can be expressed as

$$\vec{P} = \epsilon_0 \chi_e \vec{E},$$

where ϵ_0 is the permittivity of vacuum, and χ_e is the susceptibility of the polarizable medium. In order to calculate the current density and polarization, it is necessary to determine the electric field, which is the negative gradient of the electric potential. It is shown that polarization does not enter into this calculation, and that the expressions developed by Roman (1931) for the potential in the case of current flow in a two-layered earth model are valid. This implies that the ground has been energized long enough so that the current has reached a steady-state value. Under these conditions it is customary to treat the current-flow problem by the electrostatic analogy in which charges of $I\rho_1/2\pi$ replace the current electrodes.

After the current is shut off, the polarization of the aquifer is the only source of potential difference at the potential electrodes. The derivation, therefore, is concerned with the calculation of the potential difference at the potential electrodes due to a polarized volume element of the aquifer. The potential $d\phi$ due to the polarization of the elementary volume $d\tau$, at a distance r, is

$$d\phi = \frac{|\vec{P}| \cos\theta}{4\pi\epsilon r^2} d\tau,$$

where θ is the angle between the direction of the dipole-moment vector and the vector r. The difference of potential measured at the location of the potential electrodes due to the polarized volume element is then (Fig. 2)

$$d\phi_3 - d\phi_4 = \frac{|\vec{P}|}{4\pi\epsilon}\left(\frac{\cos\theta_3}{r_3^2} - \frac{\cos\theta_4}{r_4^2}\right) d\tau.$$

This expression must be integrated over the total volume of the aquifer to yield the measured $\Delta\phi$,

$$\Delta\phi = \int_{\text{aquifer}} \frac{|\vec{P}|}{4\pi\epsilon}\left(\frac{\cos\theta_3}{r_3^2} - \frac{\cos\theta_4}{r_4^2}\right) d\tau.$$

Finally, in order to get an expression for $\Delta\phi/V$, the quantity V must be related

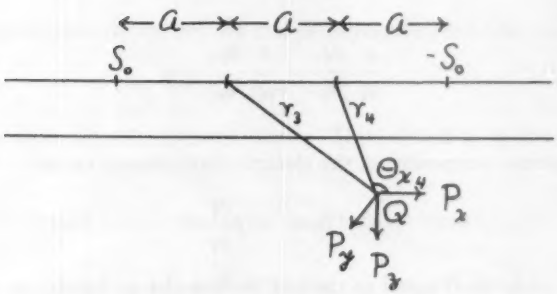

FIG. 2. Components of polarization of a polarized volume element.

to the electrical constants of the ground. Wenner's formula for the potential difference between electrodes 3 and 4 (Fig. 1) is

$$V = \frac{I\rho_a}{2\pi a},$$

where ρ_a is the apparent resistivity of the ground at a particular electrode separation a.

The expression $\Delta\phi/V$ thus obtained can be compared with data obtained from field observations.

THEORETICAL DEVELOPMENT

Proof That the Current Distribution is Independent of the Polarization

Electromagnetic theory leads to the following boundary conditions for the two-layer case:

1) The potential is steady across the interfaces, i.e.,

$$\psi_0 = \psi_1$$

at $z=0$, and (1)

$$\psi_1 = \psi_2$$

at $z=h$, where ψ_0, ψ_1, and ψ_2 are the potentials in the 0, 1, and 2 media, respectively (Fig. 3);

2) The normal component of the current-density vector

$$J_z = -\frac{1}{\rho}\frac{\partial\psi}{\partial z}$$

is steady, i.e.,

$$\frac{1}{\rho_0}\frac{\partial\psi_0}{\partial z} - \frac{1}{\rho_1}\frac{\partial\psi_1}{\partial z} = 0$$

at $z=0$, and (2)

$$\frac{1}{\rho_1}\frac{\partial \psi_1}{\partial z} - \frac{1}{\rho_2}\frac{\partial \psi_2}{\partial z} = 0$$

at $z=h$;

3) The normal component of the electric-displacement vector

$$D_z = -\epsilon \frac{\partial \psi}{\partial z}$$

changes by an amount equal to the free surface-charge density ω_f on the interface, i.e.,

$$\epsilon_0 \frac{\partial \psi_0}{\partial z} - \epsilon_1 \frac{\partial \psi_1}{\partial z} = \omega_f'$$

at $z=0$, and (3)

$$\epsilon_1 \frac{\partial \psi_1}{\partial z} - \epsilon_2 \frac{\partial \psi_2}{\partial z} = \omega_f$$

at $z=h$.

From these equations it is apparent that if neither the overburden nor the aquifer is polarizable (i.e., when $\epsilon_1=\epsilon_2=\epsilon_0$), a free surface-charge density of

$$\omega_f = \epsilon_0\left(\frac{\partial \psi_1}{\partial z} - \frac{\partial \psi_2}{\partial z}\right) \tag{4}$$

will reside on the $z=h$ interface. Since no bound charges occur in this case, ω_f represents the total charge density on the interface.

In the induced-polarization case where the lower medium is polarizable, there will be an additional contribution to the surface charge on the interface, owing to the volume polarization. A question arises as to whether this changes the current distribution between media 1 and 2. In the general case where the media are polarizable and conducting, the surface-charge density on the interface will be comprised of free charge due to the conductivity difference between the two media, and bound charge due to the difference in dielectric constants.

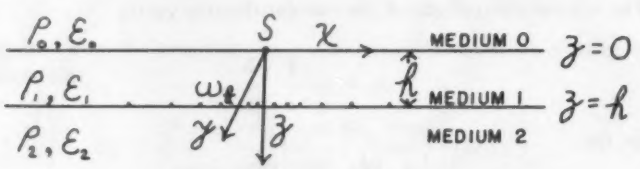

FIG. 3. Surface-charge distribution on the $z=h$ interface.

The bound surface-charge density can be developed from the relation

$$\operatorname{div} \vec{P} = -\delta', \tag{5}$$

where δ' is the bound volume-charge density. This relation gives rise to

$$P_{z_1} - P_{z_2} = \omega_b, \tag{6}$$

where ω_b is the bound surface charge on the interface. Since

$$\vec{P} = \epsilon_0 \chi_e \vec{E}, \tag{7}$$

and

$$\vec{E} = -\nabla\psi, \tag{8}$$

$$P_z = -\epsilon_0 \chi_e \frac{\partial \psi}{\partial z}. \tag{9}$$

The relation between susceptibility and permittivity is

$$\chi_e = \frac{\epsilon}{\epsilon_0} - 1, \tag{10}$$

or

$$\epsilon_0 \chi_e = \epsilon - \epsilon_0. \tag{10'}$$

Thus, the above boundary condition may be rewritten as

$$-\epsilon_1 \frac{\partial \psi_1}{\partial z} + \epsilon_0 \frac{\partial \psi_1}{\partial z} + \epsilon_2 \frac{\partial \psi_2}{\partial z} - \epsilon_0 \frac{\partial \psi_2}{\partial z} = \omega_b. \tag{11}$$

The total surface charge ω is the sum of ω_f and ω_b;

$$\omega = \epsilon_0 \frac{\partial \psi_1}{\partial z} - \epsilon_0 \frac{\partial \psi_2}{\partial z}. \tag{12}$$

Equation (12) is obviously the expression for the surface-charge density in the case of nonpolarizable media (equation 4).

This shows that the current distribution is not affected by the dielectric polarization. Therefore, the method used by Roman (1931) for determining the potentials in a horizontally stratified earth model is valid for the polarization problem.

Computation of the Induced-Polarization Quantity $\Delta\phi/V$

Probably the simplest way of determining the potentials in the different media for the two-layer case is the image method (Roman, 1931). In Figure 4 the point

S_0, taken as the origin, is a constant point charge representing the current electrode after the establishment of the steady-state condition. M_2 is its image across the interface between medium 1 and medium 2. N_2 is the image of M_2 across the interface between medium 0 and medium 1, etc. Thus, two infinite series of images, N_{2k} and M_{2k}, result. It is seen that N_{2k} and M_{2k} are at a distance of $2kh(k=1, 2, 3, \cdots)$ from the origin at S_0.

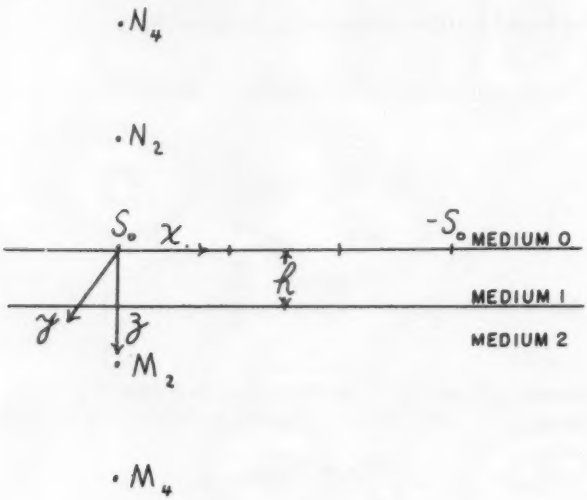

FIG. 4. Images of current source.

Roman (1931) has shown that the potential ψ_0 at any point inside medium 0 is given by

$$\psi_0 = \frac{{}_0S_0}{\sqrt{x^2+y^2+z^2}} + \sum_{k=1}^{\infty} \frac{{}_0M_{2k}}{\sqrt{x^2+y^2+(2kh-z)^2}}, \tag{13}$$

at a point in the overburden by

$$\psi_1 = \frac{{}_1S_0}{\sqrt{x^2+y^2+z^2}} + \sum_{k=1}^{\infty}\left(\frac{{}_1M_{2k}}{\sqrt{x^2+y^2+(2kh-z)^2}} + \frac{{}_1N_{2k}}{\sqrt{x^2+y^2+(2kh+z)^2}}\right), \tag{14}$$

and in the aquifer by

$$\psi_2 = \frac{{}_2S_0}{\sqrt{x^2+y^2+z^2}} + \sum_{k=1}^{\infty} \frac{{}_2N_{2k}}{\sqrt{x^2+y^2+(2kh+z)^2}}. \tag{15}$$

The subscripts before the constants S, N, and M indicate the medium in which the potential is being described. The subscripts after the constants are indicative

of the distance $2kh$ of the particular image from the origin. In order to get the expression for ψ_2 in terms of more fundamental quantities, we must evaluate the source and image constants by substituting the above potential relations into the boundary conditions, equations (1) and (2).

Solving for these constants and substituting them into equation (15), the expression for the potential in the aquifer becomes

$$\psi_2 = \frac{I\rho_1(Q_2 + 1)}{2\pi} \sum_{k=0}^{\infty} \frac{Q_2^k}{\sqrt{x^2 + y^2 + (2kh + z)^2}}, \tag{16}$$

where

$$Q_2 = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}.$$

Since there are two current electrodes in the Wenner configuration, the total potential in medium 2 results from the sum of the potentials due to each electrode. In the Wenner configuration the coordinates of the other current electrode are $(3a, 0, 0)$, and the distance between it and any point P is

$$\sqrt{(x - 3a)^2 + y^2 + z^2}.$$

Thus, the total potential ψ_2 can be written as

$$\psi_2 = \frac{I\rho_1(Q_2+1)}{2\pi} \sum_{k=0}^{\infty} Q_2^k \left(\frac{1}{\sqrt{x^2+y^2+(2kh+z)^2}} - \frac{1}{\sqrt{(x-3a)^2+y^2+(2kh+z)^2}} \right). \tag{17}$$

From equations (7) and (8), the expression for the dipole moment is

$$\vec{P} = A_2 \nabla \psi, \tag{18}$$

where A_2 contains the polarization constants. Considering the components of $\boldsymbol{P}$ separately,

$$P_x = A_2 \frac{\partial \Psi_2}{\partial x}, \tag{19a}$$

$$P_y = A_2 \frac{\partial \Psi_2}{\partial y}, \tag{19b}$$

and

$$P_z = A_2 \frac{\partial \Psi_2}{\partial z}. \tag{19c}$$

Differentiating equation (17) and substituting it into (19) yields

$$P_x = \frac{IA_2\rho_1(Q_2 + 1)}{2\pi}$$

(Continued on next page)

$$\sum_{k=0}^{\infty} Q_2{}^k \left[\frac{x - 3a}{[(x-3a)^2 + y^2 + (2kh + z)^2]^{3/2}} - \frac{x}{[x^2 + y^2 + (2kh + z)^2]^{3/2}} \right], \quad (20a)$$

$$P_y = \frac{IA_2\rho_1(Q_2 + 1)}{2\pi}$$

$$\sum_{k=0}^{\infty} Q_2{}^k \left[\frac{y}{[(x-3a)^2 + y^2 + (2kh + z)^2]^{3/2}} - \frac{y}{[x^2 + y^2 + (2kh + z)^2]^{3/2}} \right], \quad (20b)$$

and

$$P_z = \frac{IA_2\rho_1(Q_2 + 1)}{2\pi}$$

$$\sum_{k=0}^{\infty} Q_2{}^k \left[\frac{2kh + z}{[(x-3a)^2 + y^2 + (2kh + z)^2]^{3/2}} - \frac{2kh + z}{[x^2 + y^2 + (2kh + z)^2]^{3/2}} \right]. \quad (20c)$$

The relation between $\Delta\phi$ and P is

$$\Delta\phi = \int_{\text{aquifer}} \frac{|\vec{P}|}{4\pi\epsilon} \left(\frac{\cos\theta_3}{r_3{}^2} - \frac{\cos\theta_4}{r_4{}^2} \right) d\tau. \quad (21)$$

From Figure 2 it can be seen that

$$r_3 = \sqrt{(x-a)^2 + y^2 + z^2}, \quad (22)$$

and

$$r_4 = \sqrt{(x-2a)^2 + y^2 + z^2}$$

and that

$$\begin{aligned} \cos\theta_{x_3} &= -\frac{x-a}{r_3}, & \cos\theta_{x_4} &= -\frac{x-2a}{r_4}, \\ \cos\theta_{y_3} &= -\frac{y}{r_3}, & \cos\theta_{y_4} &= -\frac{y}{r_4}, \\ \cos\theta_{z_3} &= -\frac{z}{r_3}, & \cos\theta_{z_4} &= -\frac{z}{r_4}. \end{aligned} \quad (23)$$

Using equation (21), the difference in potential between the nonpolarizing electrodes is

$$\Delta\phi_2 = \int_{\text{aquifer}} \frac{1}{4\pi\epsilon} \left[P_x \left(\frac{\cos\theta_{x_3}}{r_3{}^2} - \frac{\cos\theta_{x_4}}{r_4{}^2} \right) + P_y \left(\frac{\cos\theta_{y_3}}{r_3{}^2} - \frac{\cos\theta_{y_4}}{r_4{}^2} \right) + P_z \left(\frac{\cos\theta_{z_3}}{r_3{}^2} - \frac{\cos\theta_{z_4}}{r_4{}^2} \right) \right] d\tau. \quad (24)$$

The quantity ϵ is related to both ϵ_1 and ϵ_2. Its value will be discussed later.

Substituting equations (20), (22), and (23) into equation (24), we have an expression for the potential difference between the nonpolarizing electrodes due to a polarizable aquifer:

$$\Delta\phi_2 = \frac{IA_2\rho_1(Q_2+1)}{8\pi^2\epsilon}\int_h^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\sum_{k=0}^{\infty}Q_2^k$$

$$\left\{\left(\frac{x-3a}{[(x-3a)^2+y^2+(2kh+z)^2]^{3/2}}-\frac{x}{[x^2+y^2+(2kh+z)^2]^{3/2}}\right)\right.$$
$$\left(\frac{x-2a}{[(x-2a)^2+y^2+z^2]^{3/2}}-\frac{x-a}{[(x-a)^2+y^2+z^2]^{3/2}}\right)$$
$$+\left(\frac{y}{[(x-3a)^2+y^2+(2kh+z)^2]^{3/2}}-\frac{y}{[x^2+y^2+(2kh+z)^2]^{3/2}}\right) \tag{25}$$
$$\left(\frac{y}{[(x-2a)^2+y^2+z^2]^{3/2}}-\frac{y}{[(x-a)^2+y^2+z^2]^{3/2}}\right)$$
$$+\left(\frac{2kh+z}{[(x-3a)^2+y^2+(2kh+z)^2]^{3/2}}-\frac{2kh+z}{[x^2+y^2+(2kh+z)^2]^{3/2}}\right)$$
$$\left.\left(\frac{z}{[(x-2a)^2+y^2+z^2]^{3/2}}-\frac{z}{[(x-a)^2+v^2+z^2]^{3/2}}\right)\right\}dxdydz,$$

or

$$\Delta\phi_2 = \frac{IA_2\rho_1(Q_2+1)}{8\pi^2\epsilon}\int_h^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\sum_{k=0}^{\infty}Q_2^k$$

$$\left[\frac{(x-3a)(x-2a)+y^2+(2kh+z)z}{\{[(x-3a)^2+y^2+(2kh+z)^2][(x-2a)^2+y^2+z^2]\}^{3/2}}\right.$$
$$-\frac{(x-3a)(x-a)+y^2+(2kh+z)z}{\{[(x-3a)^2+y^2+(2kh+z)^2][(x-a)^2+y^2+z^2]\}^{3/2}}$$
$$-\frac{x(x-2a)+y^2+(2kh+z)z}{\{[x^2+y^2+(2kh+z)^2][(x-2a)^2+y^2+z^2]\}^{3/2}} \tag{26}$$
$$\left.+\frac{x(x-a)+y^2+(2kh+z)z}{\{[x^2+y^2+(2kh+z)^2][(x-a)^2+y^2+z^2]\}^{3/2}}\right]dxdydz.$$

When $3a-x$ is substituted for x in the appropriate pair of the four integrals, which is justified since the interval of integration extends from $-\infty$ to $+\infty$, equation (26) simplifies to

$$\Delta\phi_2 = \frac{IA_2\rho_1(Q_2+1)}{4\pi^2\epsilon}\int_h^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\sum_{k=0}^{\infty}Q_2{}^k\left\{\frac{x(x-a)+y^2+(2kh+z)z}{[x^2+y^2+(2kh+z)^2]^{3/2}}\right.$$
$$\left.-\frac{(x-3a)(x-a)+y^2+(2kh+z)z}{[(x-3a)^2+y^2+(2kh+z)^2]^{3/2}}\right\}\frac{dxdydz}{[(x-a)^2+y^2+z^2]^{3/2}}. \tag{27}$$

Since the expression is symmetrical with respect to the y coordinate,

$$\int_{-\infty}^{+\infty}f(y^2)dy = 2\int_0^{+\infty}f(y^2)dy.$$

Thus,

$$\Delta\phi_2 = \frac{IA_2\rho_1(Q_2+1)}{2\pi^2\epsilon}\int_h^{+\infty}\int_0^{+\infty}\int_{-\infty}^{+\infty}\sum_{k=0}^{\infty}Q_2{}^k\left(\frac{x(x-a)+y^2+(2kh+z)z}{[x^2+y^2+(2kh+z)^2]^{3/2}}\right.$$
$$\left.-\frac{(x-3a)(x-a)+y^2+(2kh+z)z}{[(x-3a)^2+y^2+(2kh+z)^2]^{3/2}}\right)\frac{dxdydz}{[(x-a)^2+y^2+z^2]^{3/2}}. \tag{28}$$

Coordinates of the integrand are transformed into units of a by substituting $x=a\xi$, $y=a\sigma$, $z=a\delta$, and $h=aH$.

$$\Delta\phi_2 = \frac{IA_2\rho_1(Q_2+1)}{2\pi^2\epsilon a}\int_H^{+\infty}\int_0^{+\infty}\int_{-\infty}^{+\infty}\sum_{k=0}^{\infty}Q_2{}^k\left[\frac{\xi(\xi-1)+\sigma^2+(2kH+\delta)\delta}{[\xi^2+\sigma^2+{}_12kH+\delta)^2]^{3/2}}\right.$$
$$\left.-\frac{(\xi-3)(\xi-1)+\sigma^2+(2kH+\delta)\delta}{[(\xi-3)^2+\sigma^2+(2kH+\delta)^2]^{3/2}}\right]\frac{d\xi d\sigma d\delta}{[(\xi-1)^2+\sigma^2+\delta^2]^{3/2}}. \tag{29}$$

Since

$$V = \frac{I\rho_a}{2\pi a}, \tag{30}$$

$\Delta\phi_2/V$ finally becomes

$$\frac{\Delta\phi_2}{V} = \frac{A_2(Q_2+1)}{\pi\epsilon}\,\frac{\rho_1}{\rho_a}\int_H^{+\infty}\int_0^{+\infty}\int_{-\infty}^{+\infty}\sum_{k=0}^{\infty}Q_2{}^k\left[\frac{\xi(\xi-1)+\sigma^2+(2kH+\delta)\delta}{[\xi^2+\sigma^2+(2kH+\delta)^2]^{3/2}}\right.$$
$$\left.-\frac{(\xi-3)(\xi-1)+\sigma^2+(2kH+\delta)\delta}{[(\xi-3)^2+\sigma^2+(2kH+\delta)^2]^{3/2}}\right]\frac{d\xi d\sigma d\delta}{[(\xi-1)^2+\sigma^2+\delta^2]^{3/2}}. \tag{31}$$

Interchanging summation and integration signs,

$$\frac{\Delta\phi_2}{V} = \frac{A_2(Q_2+1)}{\pi\epsilon}\,\frac{\rho_1}{\rho_a}\sum_{k=0}^{\infty}Q_2{}^k\int_H^{+\infty}\int_0^{+\infty}\int_{-\infty}^{+\infty}\left[\frac{\xi(\xi-1)+\sigma^2+(2kH+\delta)\delta}{[\xi^2+\sigma^2+(2kH+\delta)^2]^{3/2}}\right.$$
$$\left.-\frac{(\xi-3)(\xi-1)+\sigma^2+(2kH+\delta)\delta}{[(\xi-3)^2+\sigma^2+(2kH+\delta)^2]^{3/2}}\right]\frac{d\xi d\sigma d\delta}{[(\xi-1)^2+\sigma^2+\delta^2]^{3/2}}. \tag{32}$$

The integral portion of equation (32) was solved numerically on a digital computer at Los Alamos, New Mexico. A mesh system including 37 values of ξ, 23 values of σ, and 19 values of δ (a total of 16,169 mesh points) spaced in the manner indicated in Table I, gave values of the integral to within a maximum error of 10 percent.

The integral was evaluated for values of $H=0.1$, 0.2, 0.4, 0.8, 1.6, and 3.2. For $H=0.1$, as many as 12 terms of the series are required to maintain less than 10 percent error. As the values of H increase, the rate of convergence increases, so that fewer terms are required. The rate of convergence decreases with increasing magnitude of Q_2. This may partially explain the lack of conformity of the $Q_2=-0.9$ curve (Fig. 6).

Values of ρ_1/ρ_a for $Q_2=\pm 0.3$, ± 0.6, ± 0.9 were obtained from Roman's tables (Roman, 1934). The values of ρ_1/ρ_a at $a/h=10$ had to be approximated; at this point, therefore, $\Delta\phi_2/V$ may exceed the 10-percent maximum error.

Table II contains the computed values of the integral of equation (32). Table III contains the computed values of

$$\frac{\pi\epsilon}{A_2}\frac{\Delta\phi_2}{V}=(Q_2+1)\frac{\rho_1}{\rho_a}\sum_{k=0}^{\infty}Q_2^k\int_H^{+\infty}\int_0^{+\infty}\int_{-\infty}^{+\infty}\left[\frac{\xi(\xi-1)+\sigma^2+(2kH+\delta)\delta}{[\xi^2+\sigma^2+(2kH+\delta)^2]^{3/2}}\right.$$
$$\left.-\frac{(\xi-3)(\xi-1)+\sigma^2+(2kH+\delta)\delta}{[(\xi-3)^2+\sigma^2+(2kH+\delta)^2]^{3/2}}\right]\frac{d\xi d\sigma d\delta}{[(\xi-1)^2+\sigma^2+\delta^2]^{3/2}}. \tag{33}$$

Figures 5 and 6 are plots of the values taken from Table III, where a/h is plotted on the abscissa. Because $\Delta\phi_2/V$ differs from the values of the ordinate only by

TABLE I

MESH SYSTEM

ξ	$-1\frac{3}{8}(3/16)+\frac{1}{2}$;	$\frac{1}{2}(3/32)1\frac{1}{8}$;	$1\frac{1}{8}(3/16)4\frac{1}{2}$
σ	0(0.1)1;	1(0.2)2.2;	2.2(0.4)4.6
δ	0.1(.05)0.4;	0.4(0.1)0.8;	0.8(0.4)4.0

TABLE II

COMPUTED VALUES OF THE INTEGRAL IN EQUATION (32)

Q_2 \ H	a/h	0.1	0.2	0.4	0.8	1.6	3.2
		10	5	2.5	1.25	0.625	0.3125
−0.9		0.8149	0.8017	0.6892	0.3432	0.0753	0.0052
−0.6		0.9714	0.9233	0.7582	0.3603	0.0774	0.0052
−0.3		1.1776	1.0938	0.8439	0.3805	0.0793	0.0054
0.0		1.4944	1.3326	0.9517	0.4041	0.0820	0.0054
+0.3		2.0304	1.6888	1.0926	0.4325	0.0847	0.0054
+0.6		3.1039	2.2777	1.2888	0.4677	0.0883	0.0056
+0.9		6.0362	3.4363	1.5930	0.5163	0.0929	0.0057

TABLE III

COMPUTED VALUES OF THE RIGHT-HAND SIDE OF EQUATION (33)

Q_2 \ a/h	10	5	2.5	1.25	0.625	0.3125
−0.9	1.61	1.2918	0.3776	0.0591	0.0084	0.0005
−0.6	1.54	1.3513	0.7617	0.2043	0.0334	0.0021
−0.3	1.53	1.3455	0.8894	0.3159	0.0577	0.0038
0.0	1.4944	1.3326	0.9517	0.4041	0.0820	0.0054
+0.3	1.48	1.3160	0.9875	0.4761	0.1057	0.0070
+0.6	1.44	1.2955	1.0091	0.5578	0.1296	0.0088
+0.9	1.43	1.2495	1.0157	0.586	1.1540	0.0106

the constant factor $A_2/\pi\epsilon$, it exhibits the same dependence on a/h.

One of the more striking disclosures apparent from these curves is the small influence the resistivity contrast has on the magnitude of $\Delta\phi_2/V$. At the value $a/h=5$, $\Delta\phi_2/V$ is practically the same for all resistivity contrasts. Also, at this point, $\Delta\phi_2/V$ has nearly reached its full magnitude.

Vacquier et al. (1957) made measurements on a model in a tank which ap-

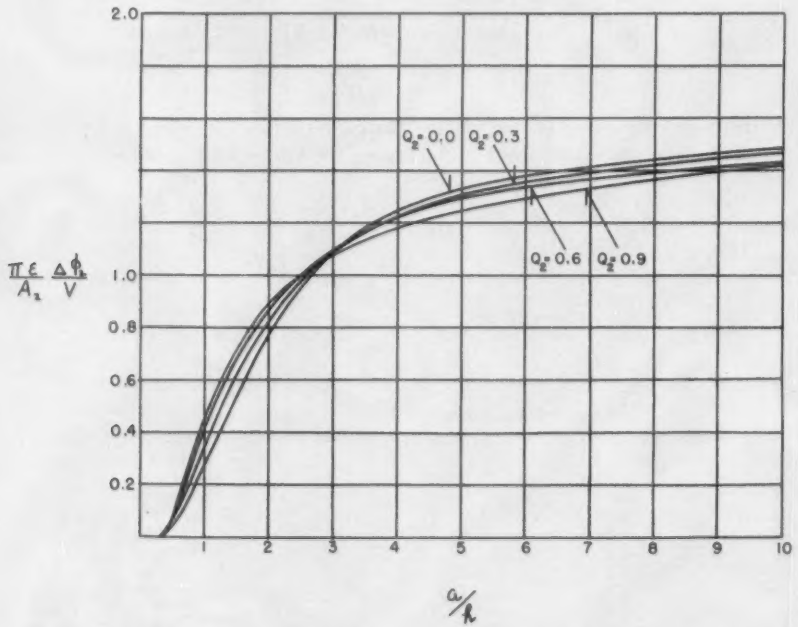

FIG. 5. Theoretical curves for the induced-polarization quantity $\Delta\phi_2/V$ vs a/h for positive Q_2 values.

proximately satisfied the conditions of the earth model for which Figures 5 and 6 were computed; namely, a nonpolarizing upper layer and a polarizable, infinitely deep lower layer. Figure 7 is a plot of the theoretical values of $Q_2 = -0.6$ and 0.0 taken from Figure 6, with the experimental results (dashed) for the same Q_2 values superimposed upon them. The scale of the ordinates of the experimental curves was adjusted to fit the theoretical curves. The fact that the experimental curves lie above the theoretical ones for the smaller values of a/h is explained by the partial leaching of salts from the polarizable medium by the overlying water which was used as the nonpolarizable overburden.

The agreement between theoretical and experimental points gives support to the validity of the assumptions made for the calculations. In particular, it seems justifiable to treat the aquifer as a dielectric medium.

THE FIELD PROBLEM

In the derivation of the induced-polarization ratio $\Delta\phi_2/V$ due to the lower medium, the current distribution is attributed to the resistivities of both media. The presence of polarizability does not affect the current distribution. It is, therefore, evident that an expression for $\Delta\phi_1/V$ for a polarizable upper layer could be added to $\Delta\phi_2/V$ for the lower layer to give the total induced-polarization effect.

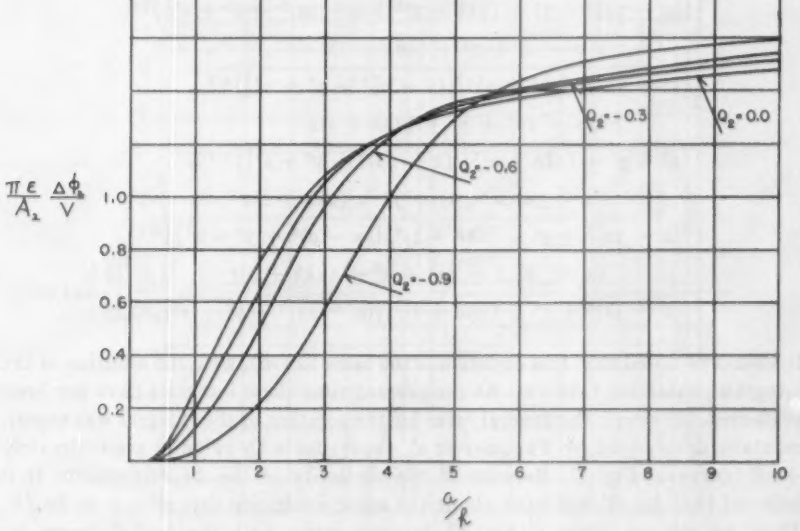

FIG. 6. Theoretical curves for the induced-polarization quantity $\Delta\phi_2/V$ vs a/h for negative Q_2 values.

Starting with equation (14), the expression for $\Delta\phi_1/V$ is derived in a manner similar to that for $\Delta\phi_2/V$.

$$\Delta\phi_1 = \frac{IA_1\rho_1}{8\pi^2\epsilon_1}\int_h^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\left\{\frac{(x-3a)(x-2a)+y^2+z^2}{\{[(x-3a)^2+y^2+z^2][(x-2a)^2+y^2+z^2]\}^{3/2}}\right.$$
$$-\frac{x(x-2a)+y^2+z^2}{\{[x^2+y^2+z^2][(x-2a)^2+y^2+z^2]\}^{3/2}}$$
$$-\frac{(x-3a)(x-a)+y^2+z^2}{\{[(x-3a)^2+y^2+z^2][(x-a)^2+y^2+z^2]\}^{3/2}}$$
$$+\frac{x(x-a)+y^2+z^2}{\{[x^2+y^2+z^2][(x-a)^2+y^2+z^2]\}^{3/2}}$$
$$+\sum_{k=1}^{\infty}Q_2{}^k\left[\frac{x(x-a)+y^2+(2kh-z)z}{\{[x^2+y^2+(2kh-z)^2][(x-a)^2+y^2+z^2]\}^{3/2}}\right.$$
$$-\frac{x(x-2a)+y^2+(2kh-z)z}{\{[x^2+y^2+(2kh-z)^2][(x-2a)^2+y^2+z^2]\}^{3/2}} \qquad (34)$$
$$-\frac{(x-3a)(x-a)+y^2+(2kh-z)z}{\{[(x-3a)^2+y^2+(2kh-z)^2][(x-a)^2+y^2+z^2]\}^{3/2}}$$
$$+\frac{(x-3a)(x-2a)+y^2+(2kh-z)z}{\{[(x-3a)^2+y^2+(2kh-z)^2][(x-2a)^2+y^2+z^2]\}^{3/2}}$$
$$+\frac{x(x-a)+y^2+(2kh+z)z}{\{[x^2+y^2+(2kh+z)^2][(x-a)^2+y^2+z^2]\}^{3/2}}$$
$$-\frac{x(x-2a)+y^2+(2kh+z)z}{\{[x^2+y^2+(2kh+z)^2][(x-2a)^2+y^2+z^2]\}^{3/2}}$$
$$-\frac{(x-3a)(x-a)+y^2+(2kh+z)z}{\{[(x-3a)^2+y^2+(2kh+z)^2][(x-a)^2+y^2+z^2]\}^{3/2}}$$
$$\left.\left.-\frac{(x-3a)(x-2a)+y^2+(2kh+z)z}{\{[(x-3a)^2+y^2+(2kh+z)^2][(x-2a)^2+y^2+z^2]\}^{3/2}}\right]\right\}dxdydz.$$

It should be noted that this equation is the same as (26), with the addition of the integrals containing $(2kh-z)$. At the present time these integrals have not been evaluated. However, the general form for the solution of the integral was experimentally determined by Vacquier et al. (1957) for a Q_2 value of approximately +0.6 (curve 1, Fig. 8). Because of the similarity of the $\Delta\phi$ expressions, it is believed that $\Delta\phi_1/V$ will have about the same resistivity dependence as $\Delta\phi_2/V$. Thus, we can use curve 1 (Fig. 8), in conjunction with the $\Delta\phi_2/V$ curves developed in this paper, to approximate field curves of different resistivity contrasts.

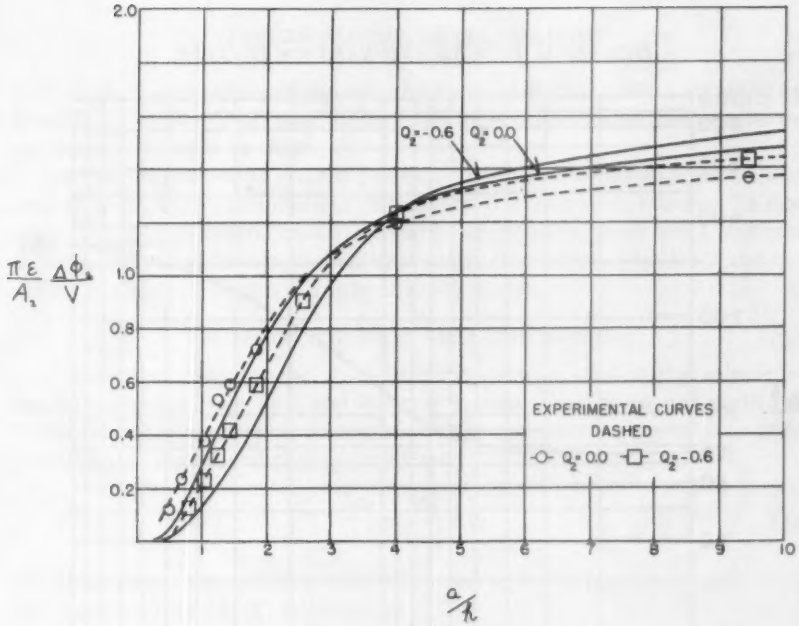

FIG. 7. Computed curves compared with measurements in a laboratory-model tank for two values of Q_2.

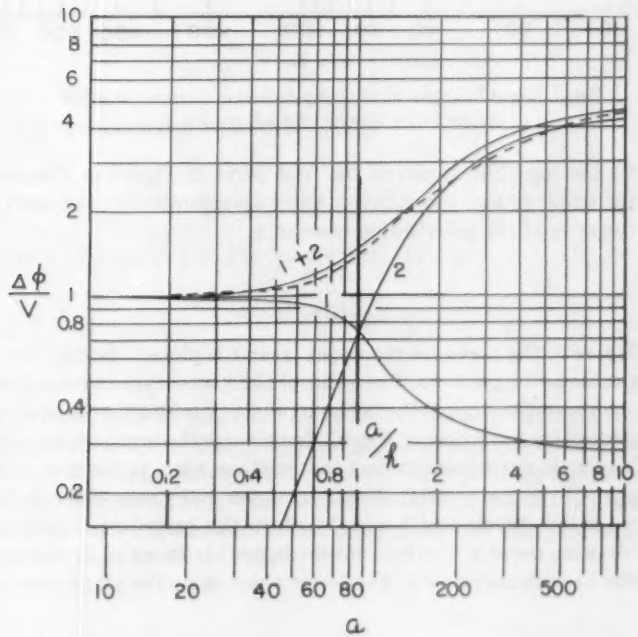

FIG. 8. Composite curve from theoretical calculation and laboratory-model experiment compared with field curve of Figure 9.

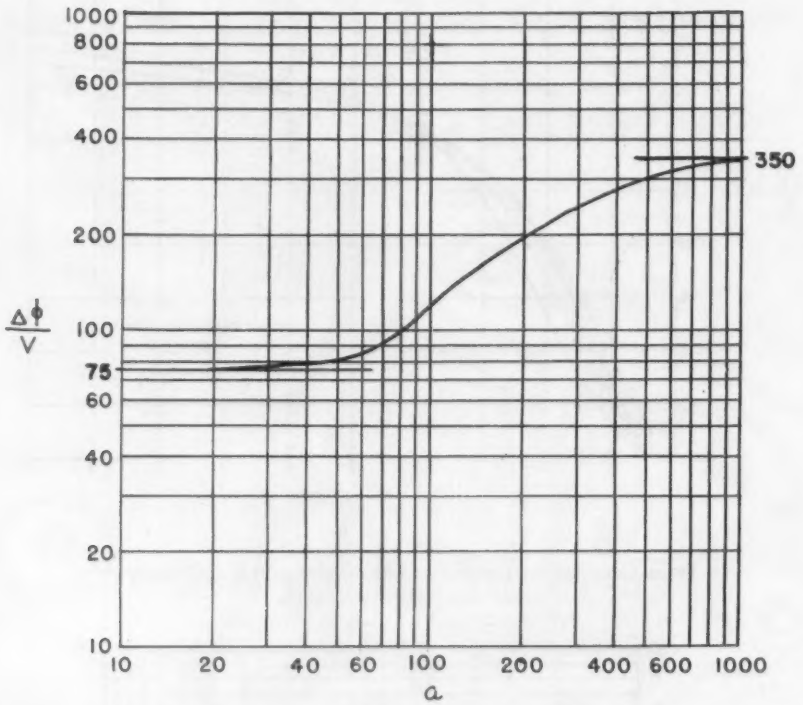

FIG. 9. Logarithmic plot of induced polarization measured at a field station vs the Wenner electrode spacing a.

Consider the logarithmic plot of the field curve in Figure 9. The curve approaches the value 75 and 350 millivolt sec/v asymptotically. The ratio $350/75 = 4.67$ is the ratio of the polarization constants

$$\frac{A_2/\epsilon_2}{A_1/\epsilon_1}.$$

Thus, in Figure 8, the curve for the upper layer 1 is plotted, letting the relative maximum value be 1 at $a/h = 0$. The value of the lower-layer curve 2 at $a/h = 10$ will be the asymptotic value of the field curve (4.67), minus the value at $a/h = 10$ of the upper-layer curve (curve 1, Fig. 8). In this case the numbers are $4.67 - 0.28 = 4.39$. This number expresses the fact that medium 2 is 4.39 times as polarizable as medium 1. Curve 2 is translated until its upper end passes through the point $\Delta\phi/V = 4.39$ millivolt/volt at $a/h = 10$. In effect, this procedure gives the scaling factor for drawing curve 2. The field curve (dashed) is drawn so that it makes the best possible fit with curve $1+2$. The lower abscissa on the graph goes with the

field curve. A comparison of the two abscissas shows that $a/h = 1$ occurs at approximately 85 feet. This, then, is the predicted depth to water. In a nearby well the depth to water is 60 feet.

The principal cause of error is probably the lack of correspondence between the initial simplifying assumptions and the actual stratigraphic relations. In most cases there will be several resistivity and polarization horizons which will commonly be interfaces between nonuniform media. The interface itself will not be a surface of sharp contrast but a zone of rapid change.

"DIELECTRIC CONSTANT" OF EARTH MATERIAL

A numerical value for the quasi-dielectric constant used in this calculation can be computed from field and laboratory measurements on wet earth materials. The maximum value calculated for the normalized instantaneous-decay potential (see Figs. 6 and 7) is approximately

$$\frac{\Delta\phi_2}{V} = \frac{A_2}{\pi\epsilon_2} 1.6, \tag{35}$$

For an electrode separation a, large compared to h, ϵ is practically equal to ϵ_2. The dielectric constant K_e is defined as

$$K_e \equiv (1 + \chi_e). \tag{36}$$

and

$$\epsilon_2 = \epsilon_0(1 + \chi_e). \tag{36'}$$

It follows that

$$\frac{\Delta\phi_2}{V} = \frac{1}{\pi}\left(1 - \frac{1}{K_{e_2}}\right)1.6\,, \tag{37}$$

where 1.6 is the maximum value attained by

$$\frac{\pi\epsilon}{A_2}\frac{\Delta\phi_2}{V}$$

as evidenced by Figures 5 and 6. Solving (37) for K_{e2},

$$K_{e_2} = \frac{1.6}{1.6 - \pi\dfrac{\Delta\phi}{V}}\,. \tag{38}$$

The maximum values obtained for $\Delta\phi/V$ from field data are approximately 10 millivolts per volt. Substituting this into (38), $K_e = 1.02$. Since K_e is rather close to unity, $\epsilon_2 \cong \epsilon_0$. Thus, ϵ in equation (24) and subsequent equations is also approximately equal to ϵ_0. This result seems incompatible with the low-frequency value of 10^6 found by Keller and Lecastro (1955) for the dielectric constant, and the value 10^8 found by Evjen (1948).

This difference of factors of 10^6 and 10^8 is interpreted as a divergence of two views on the definition of dielectric constant in moist earth materials. In this study the mathematical treatment was carried out by the equations of electrostatics for the sake of convenience. This treatment is valid only as long as one does not try to interpret the shape of the voltage-relaxation curve. This curve is not exponential but hyperbolic (Vacquier et al., 1957) and is characteristic of ion-diffusion phenomena of electrochemistry. The dielectric constant is a measure of the displacement of bound charge in an electric field; it is not related to concentration and diffusion potentials. For example, a condenser and a storage battery store electrical energy, but we do not ascribe the energy in the battery to the dielectric polarization of the electrolyte. The modest value of 1.02 for the dielectric constant obtained in this analysis is not necessarily related to any actual displacement of bound charges in the aquifer. It simply means that the induced electrochemical concentration and diffusion potentials are small compared to the potentials due to the energizing current.

CONCLUSION

A theoretical solution has been given for the two-layered induced-electrical-polarization problem for the case of a nonpolarizable upper layer and a polarizable, infinitely deep lower layer. This solution has been shown to be in good agreement with data from a laboratory model and with a selected field curve.

It is believed that an attempt at a mathematical solution of a problem involving more than two layers would reach impractical proportions at the machine-computation stage. More complex distributions than the one treated in this paper are best studied on laboratory models.

ACKNOWLEDGMENT

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PATENTS IN THE SERVICE OF GEOPHYSICS*

O. F. RITZMANN†

ABSTRACT

This paper presents a general discussion of the significance of patents and how they affect geophysical operations. Patents have become an important part of our technical literature. In spite of the exclusive character of the patent grant, the geophysical exploration art has been very little handicapped by patents or patent controversies. The inventions disclosed in patents have served as stepping stones for advancing the practical application of all branches of physics to exploration techniques.

The main purpose of this paper is to discuss briefly the role of patents in advancing the arts with particular reference to the geophysical art. Many of the things I shall mention will be familiar to many of you and will be of interest only to the younger geophysicists. More particularly I wish to call attention to patents as a particularly fertile source of ideas in the geophysical art and also discuss briefly the economic aspect of patents.

Article 1 Section 8, of the Constitution says "The Congress shall have the power to promote the progress of science and useful arts, by securing for limited times to authors and inventors the exclusive right to their respective writings and discoveries." This is the basis of our patent statutes.

In formulating the patent laws and the rather complex jurisprudence surrounding patents which has since developed, one basic underlying principle always stands out, namely, in order to harvest the benefits bestowed on an inventor by this Article of the Constitution, the inventor must disclose his invention for the public benefit so as "to promote the progress of science and useful arts." The patent laws form the basis of a special relationship between the inventor and the government. The terms of this relationship are: The inventor teaches the invention to the public for the public good, and the government gives the inventor the right to exclude others from practicing the invention for a limited time. This "right" is called a patent and its term is 17 years.

Numerous statutes have been enacted by Congress for the purpose of implementing the constitutional provision concerning "inventors" and their "discoveries." According to our patent statutes not all "discoveries" are patentable subject matter. The dictionary definition of invention does not mention patents, but patentable invention is a special variety. The exploration team of a producing company may exercise inventiveness of a very high degree in analyzing all the geophysical data at hand and in spotting a wildcat well, but this is a mental process which is *not patentable*. Similarly a tax accountant may exercise inventiveness of a high degree in guiding the financial affairs of a corporation to save it

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amounts often comparable in value to the production of a successful oil well, but this also is *not patentable* subject matter.

Our patent statute says that a patent may be obtained on any new and useful art (more commonly called a process), machine (more commonly called apparatus), manufacture or composition of matter (more commonly called a product), or any new and useful improvement thereof. (Included also are certain categories of plants and also ornamental designs which do not concern us here.) If the discovery falls within one or more of these classes and meets certain other prescribed requirements, it becomes patentable subject matter and the inventor may, by successful prosecution of a patent application obtain a patent on his invention.

The patent statutes also prescribe certain other requirements of a "discovery" in order that it be patentable. It must be new, it must be useful, and it must be an "invention." The requirement of newness (commonly called novelty) means that the invention must not have been known before. The inventor to obtain a valid patent must also be the "first" inventor. Usually this means that he must be the first one in point of time to complete the invention, although the law recognizes certain mitigating circumstances. The inventor must not have abandoned the invention nor effectively released it into the public domain. The invention must be useful. Finally the "discovery" must truly be an "invention." The legal meaning of "invention" has defied adequate definition, but an "invention" requires something over and above the exercise of mere ordinary skill. In addition there are certain other factors recognized by law which contribute to make a patentable invention.

I shall use the term "inventor" in the very broadest sense to mean the owner of the patent right or anyone who has obtained the right to use the invention. The legal process of obtaining a patent starts with the filing of a patent application which discloses the invention, i.e. describes it in complete detail. The detail must be sufficiently complete so that the public can from the description practice the invention after the end of the 17 year patented period. The drafting of the patent application and its prosecution to patent are functions of the patent attorney and they are familiar to the many geophysicists who have made patentable inventions. The patent thus serves as a vehicle for bringing the invention before the public.

A patent specification must completely describe the invention so that anyone with reasonable skill in the art can understand it, and by following the description accomplish the useful ends or solve the problem for which the invention was intended. This means that there is no such thing as a "secret patent" (except for certain special situations now recognized in the field of atomic energy). Printed copies of patents may be purchased from the U. S. Patent Office for 25 cents each, and I can assure you that for the interested person some of them are bargains in exposition at that price. Copies are maintained for reference at all government depository libraries located in many large cities throughout the country. Through

exchange and purchase, copies are available in offices of foreign governments all over the world. The United States alone has issued a little over $2\frac{3}{4}$ million patents to date, the present rate being roughly a thousand per week. The industrial foreign countries issue many patents too and many also sell printed copies. Patents thus become a vehicle for the dissemination of information just as periodicals or books.

All these patents represent a tremendous body of knowledge for anyone to read if they want the information. The SEG has attempted to keep readers of GEOPHYSICS informed of at least the important U. S. patents which pertain directly to exploration geophysics by publishing short abstracts with which you are familiar. There are a great many additional ones that are more remotely connected with the art that are merely classified and listed by number. The Editor of GEOPHYSICS would welcome suggestions for making this material more useful to geophysicists.

In considering printed patents as part of our technical literature, one finds an important characteristic not found in most technical papers. Omitting from consideration the so-called "claims" at the end of the patent, and the legal verbiage now practically obsolete in technical patents, the specification of a patent is usually directed at the solution of a very special practical problem. Even if the invention is a solution of a broad fundamental problem, the patent law still requires the patent specification to explain how the invention is embodied in a particular example. The sum total of patent specifications on a particular subject will therefore give detailed information on construction features and solutions of practical problems which are sometimes obscure at first glance, but nevertheless important, and it will also give one or more specific examples. In other words, the patent literature is much more of a practical handbook-type of material than the usual scientific literature article. Except possibly for case-history articles, most literature articles do not go into as much detail as the average patent specification. Furthermore the degree of detail in patents is necessarily increasing as the art becomes more highly developed.

Patent attorneys are in the habit of determining the novelty of an invention by making patent searches. They often refrain from searching the literature partly because it is not so well classified and therefore harder to find and in many cases also because the inventor or his research staff is presumed to be familiar with the literature. However, United States patents are classified very carefully by the Patent Office, and for this reason the patents as literature may be a tremendous help when one is starting off on a new development. A state-of-the-art patent search may solve the problem by either presenting a solution or by presenting partial solutions which suggest avenues of approach to the solution, or even by suggesting several solutions which only need evaluation in terms of present conditions or costs. For this reason, an important service obtained from the patent art is a kind of practical perspective which it gives the reader. Oftentimes it is found that the particular problem under consideration never arose before,

simply because the technology had not previously developed to this point. However, one often finds from the patent art that a similar problem in related fields was solved in several ways, either of which may be applicable as found or with slight obvious modification. Associated problems encountered in the related fields will probably also be encountered here and other patents will suggest their solutions. In this way altogether a great deal of information is obtainable from the patent art and by making use of it the engineer will find many helpful hints if not ready-made solutions.

By thus familiarizing himself with the patented inventions already made in his field of endeavor, as well as in related fields and also the background literature, the engineer is enabled to arrive at better inventions quicker and more directly. Moreover, he has a degree of assurance that the results of his work will in turn be patentable. Every patent attorney can site instances in his experience where an elaborate and expensive research project was completed and then someone decided that the fruits of the work should be patented, only to find that the invention was anticipated in the patent art. Much of the research expense, and the eventual disappointment at not being able to protect its results adequately, can often be avoided by an early thorough-going patent-art search. The expense of such a search is not large, in fact it is small in terms of present-day research costs.

There is another very useful result of a patent-art search. Many of us are prone to justifiable enthusiasm over our own inventions. In geophysical prospecting some of our inventions literally have haloes. However, no one can rightly claim as his own invention something which he knows has been done before. Therefore, for a wholesome evaluation of our own inventions, it is imperative that the inventor know what has gone before. This knowledge raises the standard of invention which is a desirable condition for the technical advance of the art. It is my opinion that in the geophysical prospecting art, a relatively high standard of invention has existed and for this reason the geophysical patent art is all the more valuable. This is not to say that minor inventions are not patented by geophysicists, but rather means that the patented inventions are characterized by a certain outstanding quality of ingenuity above average among patents. I believe this is due to the fact that geophysicists as a group are broadly trained and well informed. As a consequence there has been relatively little patent litigation and at the same time the inventions have been well able to carry a justifiable royalty.

The foregoing discussion extolls the advantages of the patent art as source material. However, a patent is a limited form of monopoly and the engineer and executive may well ask, "What good are all these patented inventions to me when someone else has the exclusive right to them." The answer lies behind the purpose in granting a patent—namely to promote the useful arts. From this, one may assume that the benefits of the invention must in some manner be made available to the public. There are several ways in which it eventually becomes

available. First the patent may have expired, therefore it is free for all to use. This is easily determined from the date. Second, the restrictive sphere of the patent is measured by its claims, and these are seldom as broad as the specification would lead the uninitiated engineer to believe. The interpretation of the claims is in the province of the patent attorney, for it involves many legal considerations. In short, the restrictive area usually is much smaller than what the patent teaches as a publication. Third, some or all of the claims of the patent may be invalid for various reasons which may come to light after the patent was granted, and it may even have been adjudicated as invalid or may have been dedicated to the public for some reason. The patent attorney can usually determine the status of a patent, and he may need the assistance of a competent engineer if a definitive validity opinion is to be made, although a final decision as to validity lies only in the courts. Fourth, and most important, licenses on reasonable terms are commonly available, in the oil industry at least.

The inventor's right to exclude others from practicing his invention includes making, using or selling it. A distinction arises here in that the inventor can exclude others from practicing his invention, but note that his patent does not guarantee him the right to practice the invention himself. This arises because in this complex age his invention often makes use of other inventions on which others have been granted patents before him and which patents have not yet expired. As an example, an improved AVC circuit for a seismic amplifier may be subservient to a process patent covering the use of AVC in seismic operations, which in turn may as a practical matter be subservient to one or more patents on components (e.g. vacuum tubes or transistors). However, in the actually-occurring sequence of these inventions, each one was a step forward in the progress of the useful arts and each justified a patent. Each patent secures for the inventor a monopoly only on the particular step forward made by the inventor.

There are various ways open by which an inventor may acquire licenses under underlying patents. He may purchase components made by the patentees of these components or their licensees, he may pay a royalty to some patentee from whom he buys nothing else, or he may otherwise acquire the necessary right as for example by trading other rights.

At first glance it may seem that for a complex device, like the improved AVC circuit for a transistorized seismic amplifier previously mentioned, there would be so many outstanding patents that it would become almost a hopeless task to unravel them all. In some instances this is literally true and it requires the expert attention of both engineer and patent attorney. Fortunately however the process is usually very simple. The inventor purchases components from underlying patentees or from manufacturers licensed by such patentees, and he obtains whatever licenses he needs under process patents covering his operation. A similar procedure may be followed by someone who is not the inventor. Alternatively others may contract to have the work done by a licensed contractor who in turn obtains the necessary licenses. Note that in all cases in which business is done in

good faith, the eventual beneficiary of the inventions involved is either directly or indirectly paying compensation to all of the underlying patentees that have unexpired patents. In this manner the various inventors whose inventions formed the building blocks leading to the latest invention are all rewarded. It is apparent that the latest inventor is able to pay this compensation to his forerunners because he in turn is paid by the ultimate consumer, who gets a better "mousetrap." In the AVC example the consumer gets better seismic operations both in quality and quantity than he ever had before, and moreover the latest developments can not only catch ordinary "mice," but wary old bioherms as well. Of course since the patent term is limited to 17 years, there are always old patents falling into the public domain and new ones coming up at the head of the line.

If a license is to be obtained, it will in general cost something, but if the invention in question is a good one it will be well worth a reasonable cost. Of course if the patentee has already granted an exclusive license to someone else, a license may be more difficult to obtain but some sort of an arrangement can generally be worked out so as to make the invention available to someone who really wants to use it. The cost of a license or of doing without the invention will always serve as a yardstick against which the cost of developing an independent and perhaps better solution can be measured. Therefore, as a practical matter, licenses are usually available on reasonable terms. On the other hand, some patentees may feel that their business interests would be prejudiced by granting any licenses at all and they have the right to refrain from granting licenses if they wish to do so. This, of course, invites infringement and litigation. In our present rapidly-growing technology very few inventions are the sole solution to a problem and even if they are, they do not remain the sole solution for long. In any event the availability of a license and its cost to the licensee are necessarily determined in the light of the economic situation including research costs surrounding the invention. Experience has shown that a low or moderate royalty will often bring the largest total royalty return to the patent owner, while excessive royalty or other onerous license terms invite infringement and litigation which increases expenses and does not advance the industry. Experience has also shown that if the invention is a good solution, it generally costs less to pay royalty to the one who already did the research and found the answer, than it does to embark on an independent research project with the aim of duplicating the desired result.

A discussion of the economics of geophysical patents would be incomplete without mentioning what is now a classic example of enlightened handling of what might otherwise have been a very expensive patent problem to the industry. In the late twenties and early thirties, several geophysicists conceived the idea of applying AVC to seismograph recording. AVC was of course known in radio circuits, but the problem is more complicated in seismic operations because the time constant of the AVC approaches the period of the waves to be recorded. A number of more or less successful solutions were found and independent patent

applications filed. In fact some 18 geophysicists, all of whom are now familiar names in the industry, filed at about the same time. This circumstance ordinarily results in a prolonged and expensive legal proceeding in the Patent Office called "Interference," the purpose of which is to determine who is legally the "first" inventor. In this instance, because of the complexity of the various AVC systems proposed, a total of 5 interferences was declared by the Patent Office. A network of 18 people all scrapping for their precise respective patent rights in 5 overlapping interferences in a complex electronic art is so intricate that it would require many man-years to unravel it.

Rather than go to the expense of fighting out these interferences, the parties agreed to settle the scope of their respective patent rights amicably, with each party at the same time giving a free license (or immunity) to every other party. Furthermore, since some of these AVC inventions ran to components other than amplifiers, it was agreed to include all inventions in the seismic prospecting art and this eventually brought in a few more parties. The agreement became known as the Seismic Immunities Agreement. It illustrates a spirit of cooperative effort and recognition of the other fellow's position that undoubtedly saved the industry much bitter litigation and considerable expense and allowed the men to direct their attention to further improvements. There are of course many bilateral agreements of more restricted scope between the companies who use geophysics.

The industry has now entered a new era in the interpretation of geophysical data, namely the widespread use of automatic computers. Gravity data and magnetic data are natural for these machines. We now have both digital and analog computers for operating on seismograph records and several machines for pictorially portraying the seismic records in a form which more or less simulates a geological cross section. Inventions continue to appear and patent applications are being filed. With continuation of a policy of respect for the patents of others and of evaluating both our own and others' inventions in a fair light of prior inventions, common technical knowledge and practices, I feel sure that the patents on the new developments will continue to advance the geophysical art.

DEPARTMENTS

PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,777,111. K. E. Hunter. Iss. 1/8/57. App. 11/24/54. Assign. Newmont Mining Co.

Method of Geophysical Exploration. A method of detecting subsurface mineralization by setting out a fixed pair of spaced electrodes and a movable pair of spaced electrodes and measuring the phase angle between the natural earth-current potential of the movable pair with respect to that of the fixed pair at frequencies in the range 1/100 to 10 cps.

GEOCHEMICAL PROSPECTING

U. S. No. 2,772,951. D. C. Bond. Iss. 12/4/56. App. 8/2/51. Assign. The Pure Oil Co.

Logging Shales. A method of logging clayey formations by taking samples and leaching them with a solution containing replacing cations not present in the clay and determining from the remaining liquid the amount and identity of replacing ions taken up by the samples.

U. S. No. 2,773,991. E. E. Bray. Iss. 12/11/56. App. 8/28/52. Assign. Socony Mobil Oil Co., Inc.

Method of Geochemical Prospecting. A method of geochemical prospecting in which organic matter is extracted from soil samples and analyzed to determine the ratio of C_{14} to C_{12} concentration in the organic matter.

U. S. No. 2,777,799. J. B. Davis. Iss. 1/15/57. App. 8/28/52. Assign. Socony Mobil Oil Co., Inc.

Geomicrobial Prospecting Method for Petroleum. A method of determining the number of hydrocarbon-consuming bacteria in soil samples by contacting the sample with a mixture of oxygen and hydrocarbons containing some C_{14} atoms and keeping at an incubating temperature for a time and then measuring the amount of C_{14} consumed.

MAGNETIC PROSPECTING

U. S. No. 2,773,985. C. E. Hurlburt and R. H. Deahl. Iss. 12/11/56. App. 12/17/52. Assign. Bendix Aviation Corp.

Frequency Subdivider in a Flux Valve Compass System. A system for operating a flux-valve that controls a servomotor exicted from the same source as the flux-valve by connecting a frequency divider between the source and the flux-valve, the divider being a tube with a resonant circuit whose condenser cuts off the tube during alternate cycles.

U. S. No. 2,776,403. W. C. Anderson and R. I. Strough. Iss. 1/1/57. App. 7/31/44. Assign. U. S. A.

Induced Magnetization Compensator. A system for compensating equipment against the effect of induced magnetization of part of an aircraft having a flux-valve oriented parallel to the part and connected to a detector and d-c amplifier with adjustable attenuator that supplies current to a neutralizing coil around the equipment to be compensated.

U. S. No. 2,776,404. V. J. Caldecourt. Iss. 1/1/57. App. 2/28/55. Assign. The Dow Chemical Co.

Magnetometer. A device for measuring the field of a mass spectrometer having a non-metallic tube carrying a transverse coil at one end and a reference coil at the other end, the tube being oscil-

† Gulf Oil Corporation, Patent Department.

lated about a longitudinal axis by an electromechanical vibrator and the emf generated in the coil in the field compared with that in the reference coil.

U. S. No. 2,777,112. F. B. Coker and O. W. Schoenberg. Iss. 1/8/57. App. 11/12/53. Assign. United Geophysical Corp.

Magnetometer Survey Apparatus. A self-orienting total-field magnetometer carried at the end of a non-magnetic boom mounted on a vehicle by a universal joint, the boom having pneumatic cushioning cylinders which give the boom system a time constant longer than that of the magnetic orienting system.

U. S. No. 2,779,914. L. H. Rumbaugh and H. Jensen. Iss. 1/29/57. App. 6/11/46.

Magnetic Exploration Apparatus. A recording system for aeromagnetic surveying in which the magnetometer and altimeter indications are photographed on the same film with photographs of the underlying terrain.

RADIOACTIVITY PROSPECTING

U. S. No. 2,775,710. C. G. Ludeman. Iss. 12/25/56. App. 2/21/52. Assign. Texaco Development Corp.

Method of Radiological Surveying. A method of radioactivity surveying in which a number of thermoluminescent bodies are placed in shallow depressions in the ground at points of a grid over the survey area and allowed to remain for some time and later heated to release stored phosphorescence induced by subsurface radioactivity, some of the bodies being shielded to provide comparison blanks.

U. S. No. 2,776,390. N. Anton. Iss. 1/1/57. App. 11/17/53.

Radiation Detector Tube. A counter tube having a cylindrical cathode with a window at one end and an axial anode wire mounted at the opposite end, the cathode having an internal insulating sleeve at the window end or the anode having a glass or metal bead at this end in order to reduce electric field concentration at the end of the wire.

U. S. No. 2,778,947. S. A. Scherbatskoy. Iss. 1/22/57. App. 5/17/51.

Automatic Proportional Counter. A radiation detector for analyzing radiations in well logging having an associatied source of mono-energetic radiation distinct from the formation radiation energies and arranged so that the upper and lower limits of the gating elements in the analyzer are automatically varied as the response to the associated source varies.

U. S. No. 2,779,876. C. A. Tobias and H. O. Anger. Iss. 1/29/57. App. 3/3/53. Assign. U. S. A.

Radioactivity-Distribution Detector. A pinhole camera for gamma rays in which the sensitive element is an array of gamma ray counters or layers of scintillating material with an array of photocells, the counters or photocells being connected to a corresponding array of neon lights.

SEISMIC PROSPECTING

U. S. No. 2,772,746. E. Merten. Iss. 12/4/56. App. 7/18/55. Assign. Shell Development Co.

Seismic Exploration Apparatus. A device for generating a seismic disturbance having a heavy thick-walled bell which is placed on the ground and filled with an explosive gas mixture and detonated.

U. S. No. 2,773,669. J. Norman, Jr. and A. B. Hamil. Iss. 12/11/56. App. 10/29/53.

Apparatus for Placing Seismic Explosive Charges. An arrangement for drilling and loading seismic shot holes in which the explosive is in a container carried by the drill bit and the shot line is carried on a spool fastened to the drill pipe above the bit, a safety joint being provided at the end of the drill pipe so that the pipe can be pulled leaving the bit and charge at the bottom of the hole.

U. S. No. 2,774,927. W. T. Evans. Iss. 12/18/56. App. 8/25/53. Assign. Sun Oil Co.

Speed Control Apparatus. A speed control for a seismic re-recording system in which reproduction of the timing impulses of the original tape are compared with a standard frequency by a phase discriminator whose output controls the speed of the record-driving motor.

U. S. No. 2,774,955. E. J. Toomey. Iss. 12/18/56. App. 10/29/52. Assign. Texas Instruments Inc.

Apparatus for Submarine Seismic Prospecting. A cable and seismometer assembly for use in water-covered areas having a buoyed towing and conductor cable with spaced branch connecting cables attached to the ends of spar-type seismometer platforms that are weighted to float awash.

U. S. No. 2,776,560. L. W. Erath, P. E. Madeley, and S. Hatchl. Iss. 1/8/57. App. 7/3/53. Assign. Southwestern Industrial Electronics Co.

Means for Measuring and for Generating Motion. A shaking table whose table is suspended from an intermediate follower which is also driven from the same magnet system through a feed-back system so as to achieve a very low effective natural frequency on the table.

U. S. No. 2,778,623. L. D. Statham. Iss. 1/22/57. App. 12/29/52. Assign. Statham Laboratories, Inc.

Angular Accelerometer. An angular accelerometer having a cylindrical case filled with liquid which acts as the inertial mass whose relative motion with respect to the case is detected by a hinged paddle actuating a transducer.

U. S. No. 2,778,624. L. D. Statham. Iss. 1/22/57. App. 5/24/54. Assign. Statham Laboratories, Inc.

Angular Accelerometer. An angular accelerometer having a cylindrical case filled with liquid which acts as the inertial mass, relative motion of the liquid with respect to the case being detected by a spring-mounted paddle having close clearance with baffles on the case and connected to a wire-type strain gauge.

U. S. No. 2,778,905. L. D. Statham. Iss. 1/22/57. App. 8/13/51. Assign. Statham Laboratories, Inc

Motion Sensing Device. An accelerometer in which the inertial mass is a liquid and employing both viscous damping against the container walls and flow through an orifice so that the damping is independent of temperature, motion of the liquid relative to the case being detected by a paddle actuating a wire-type strain gauge.

U. S. No. 2,779,428. D. Silverman. Iss. 1/29/57. App. 7/14/51. Assign. Stanolind Oil and Gas Co.

Seismic Surveying. A seismic prospecting system in which a succession of shots is fired in prearranged arbitrary time sequence and the seismogram analyzed for cross-correlation with an impulse pattern having the same time sequence as the shots.

U. S. No. 2,780,301. J. J. Jakosky. Iss. 2/5/57. App. 6/19/52. Assign. 40% to International Geophysics, Inc., and 60% to Signal Oil and Gas Co.

Apparatus for Seismically Exploring Geological Formations Under Water. A seismic prospecting system for water-covered areas using a cable with floats and leads to the detectors and having at the middle of the spread a floating mortar which projects the charge into the air.

U. S. No. 2,781,502. D. C. Richards. Iss. 2/12/57. App. 1/21/49 and 3/18/54. Assign. Socony Mobil Oil Co., Inc.

Self-Orienting Geophone. A non-directional moving-coil seismometer having a flat coil mounted normal to a suspending cantilever rod and a magnet rotatably suspended on bearings on the same axis as the rest axis of the rod with the coil in the magnetic air gap.

U. S. No. 2,782,394. E. V. Hardway, Jr. Iss. 2/19/57. App. 12/3/53. Assign. Consolidated Electrodynamics Corp.

Electrokinetic Transducing Devices. A low frequency hydrophone having a diaphragm backed by an electrokinetic liquid communicating with a compressible member through a porous plug having electrodes which pick up the potential due to flow through the plug.

U. S. No. 2,782,865. J. J. Jakosky. Iss. 2/26/57. App. 5/6/52. Assign. 40% to International Geophysics, Inc., and 60% to Signal Oil and Gas Co.

Method of Geophysical Exploration. A system of seismic shooting using a mortar to propel the charge into the air and paying out shot line, the charge being fired at the end of the shot line while the charge is still moving so that the Doppler effect brings the dominant frequency from the explosion into the range of seismic reflections, and recording both the shock due to explosion of the propellant and of the elevated charge.

U. S. No. 2,783,118. H. E. Owen. Iss. 2/26/57. App. 8/20/53. Assign. Esso Research and Engineering Co.

Photographic Recording of Transient Signals. A system for making variable-density recordings with a galvanometer using a tapered-filament lamp whose filament is thinner and brighter at one end than at the other, the galvanometer mirror reflecting varying portions of the filament on to an apertured mask in front of the film.

U. S. No. 2,783,298. R. R. Brown and C. L. Brownlow. Iss. 2/26/57. App. 7/31/50. Assign. Phillips Petroleum Co.

Cable-Anchoring and Sealing Device. A seismometer case having a lower pointed portion and a frusto-conical cover with the cable entering a seal on the sloping surface of the cover.

U. S. No. 2,783,448. R. G. Piety. Iss. 2/26/57. App. 9/29/50. Assign. Phillips Petroleum Co.

Filter for Seismic Amplifier. A seismic prospecting system in which a band-elimination filter sharply tuned to reject a frequency of about 10 cps is interposed between the seismometer and the amplifier to prevent recording ground roll.

U. S. No. 2,783,449. R. J. Loofbourrow. Iss. 2/26/57. App. 8/28/53. Assign. The Texas Co.

Seismic Velocity Measurement. A pressure-sensitive well seismometer having a compliant hermetically-sealed envelope filled with a relatively non-compressible, low-specific-gravity di-electric liquid in which is immersed a tubular pressure-sensitive and motion-insensitive transducer.

WELL LOGGING

U. S. Re. 24,280 (Original No. 2,713,147). A. A. Stripling. Iss. 2/19/57. App. 6/29/53, 7/12/55, and 12/3/56. Assign. Socony Mobil Oil Co., Inc.

Acoustic Velocity-Electrical Resistance Correlation Well Logging. A well-logging system in which one well parameter is measured and used to generate a signal related to it by a power function and also related to an assumed normal fluid saturation of the formation, and the synthetic signal compared with a second well parameter to locate formations of abnormal fluid saturation.

U. S. No. 2,773,236. B. G. Martin and R. D. Wyckoff. Iss. 12/4/56. App. 6/3/53. Assign. Gulf Research & Development Co.

Apparatus for Detecting Ingress and Egress of Fluid in a Borehole. A device for detecting fluid loss or entry in a borehole having a pipe whose wall has a window across which is stretched a flexible partially-obstructing diaphragm carrying an electrode whose proximity to two stationary electrodes is determined by a potentiometric measurement to detect movement of the diaphragm.

U. S. No. 2,775,043. O. Suter and A. J. Abs. Iss. 12/25/56. App. 9/14/50. Assign. Technical Oil Tool Corp., Ltd.

Inclination Recording Instrument. A multi-shot inclinometer having a pivotally-supported pendulum with an upwardly-extending pointed arm and a chart which is periodically driven downward against the point and rotated a known angle between recordings.

U. S. No. 2,775,120. A. D. Bennett and D. Silverman. Iss. 12/25/56. App. 1/2/53. Assign. Stanolind Oil and Gas Co.

Fluid Entry Detection in Wells. A method of simultaneously determining the fluid-production profile and hole-size profile of an uncased well by injecting into the well a liquid whose interface can be followed and recording the interface movement at two different bottom hole pressures and comparing the records.

U. S. No. 2,775,121. A. D. Bennett and D. Silverman. Iss. 12/25/56. App. 12/29/52. Assign. Stanolind Oil and Gas Co.

Fluid Input and Diameter Measurements in Wells. A method of simultaneously determining the fluid-injection profile and hole-size profile in an uncased well by injecting a liquid whose interface can be followed and recording the interface movement at two different injection rates under the same bottom-hole pressure and comparing the records.

U. S. No. 2,776,378. A. H. Youmans. Iss. 1/1/57. App. 1/26/51. Assign. Well Surveys, Inc.

Method and Apparatus for Radioactivity Well-Logging. A radioactivity logging system using a neutron source to radiate the formations and measuring both the slow neutron and gamma ray intensities at corresponding points located a short vertical distance from the source and also at a larger distance from the source and recording the ratios between the various intensities.

U. S. No. 2,776,402. F. P. Kokesh. Iss. 1/1/57. App. 3/30/54. Assign. Schlumberger Well Surveying Corp.

Electrical Well Logging. An electric logging system in which the survey current is automatically diminished with increasing values of resistivity so as to also diminish the required auxiliary focusing current and to keep the potential measurement on scale.

U. S. No. 2,776,563. D. R. Holbert. Iss. 1/8/57. App. 7/18/55. Assign. Sinclair Oil & Gas Co.

Apparatus for Use on Locating Interface of Liquids. A device for detecting an interface between conducting and non-conducting liquids in a well having a tube with a spider that holds an open transformer core and secondary coil connected to the electrodes, the primary coil being lowered on a conductor cable to slip over the core and the primary current indicated.

U. S. No. 2,776,564. R. F. Montgomery and N. L. H. Koot. Iss. 1/8/57. App. 9/3/54.

Self-Propelled Borehole Logging Tool. A self-contained thermal logging and mechanical casing-collar counting tool that may be dropped into a well and when it reaches bottom fires a gas-releasing charge which propels the tool to the surface.

U. S. No. 2,777,746. J. V. Fredd. Iss. 1/15/57. App. 2/24/55. Assign. Otis Pressure Control, Inc.

Amplifying Recorder for Tubing Calipers. A recorder for a mechanical calipering device in which motion of the caliper arms is amplified by a pulley and cord arrangement.

U. S. No. 2,778,950. H. B. Frey, Jr. and J. Tittman. Iss. 1/22/57. App. 12/30/52. Assign. Schlumberger Well Surveying Corp.

Methods and Apparatus for Localized Neutron Logging. A system for detecting hydrogenous liquid in surface irregularities in the borehole wall having a source of slow neutrons and a detector of thermal neutrons pressed against the borehole wall so as to measure the neutrons which pass through the intervening fluid-filled surface irregularities.

U. S. No. 2,778,951. J. Tittman. Iss. 1/22/57. App. 12/12/52. Assign. Schlumberger Well Surveying Corp.

Neutron Logging Method and Apparatus. A neutron-neutron logging system having a probe pressed against the borehole wall by spring arms, the probe containing a source of high-energy neutrons in a mud-displacing material such as aluminum and an aperatured detector of thermal neutrons with the entire probe covered by a neutron shield.

U. S. No. 2,779,192. R. C. Rumble and B. A. Peters. Iss. 1/29/57. App. 12/17/53. Assign. Esso Research and Engineering Co.

Subsurface Flowmeter. A self-contained wire-line well flowmeter having a packer which seals against the borehole wall and an annular tapered flow tube with a magnetic rotameter float, a central sealed tube having a magnetic follower connected to a stylus that records on a clock-driven chart.

U. S. No. 2,779,912. H. C. Waters. Iss. 1/29/57. App. 1/24/55. Assign. Perforating Guns Atlas Corp.

Electrical Well Logging System. A commutated d-c electric logging system whose sonde has a polarized switching relay whose coil carries the current supplied to the current electrodes, the relay alternately connecting the potential leads to different pairs of potential electrodes in the sonde so that different types of resistivity curves may be obtained.

U. S. No. 2,779,913. H. C. Waters. Iss. 1/29/57. App. 1/24/55. Assign. Perforating Guns Atlas Corp.

Dual Frequency Well Logging System. A commutated d-c electric logging system in which one set of current electrodes has current interrupted at frequency f and the other set of current electrodes has current interrupted at frequency 2f, the potential signal being synchronously commutated at both frequencies and filtered to separate the signals pertaining to the different types of resistivity curves.

U. S. No. 2,779,915. J. Moon. Iss. 1/29/57. App. 1/8/52. Assign. Signal Oil and Gas Co.

Borehole Electrodes. An electric-logging sonde having a central sealed pipe with an insulating coating with electrode bands, the insulating coating being built up between bands to a larger diameter to protect the electrodes from wear.

U. S. No. 2,782,318. G. Herzog. Iss. 2/19/57. App. 8/9/51. Assign. The Texas Co.

Radioactivity Earth Exploration. An induced gamma-ray logging system using a source of neutrons and a scintillation detector whose luminophor has a vertical dimension not more than one-sixth of the distance from the source, the detector being shielded from direct radiation from the source.

U. S. No. 2,782,364. E. W. Shuler, Jr., H. F. Dunlap, and L. E. Gourley, Jr. Iss. 2/19/57. App. 10/27/52. Assign. The Atlantic Refining Co.

Method and Apparatus for Locating Displaceable Oil in Subterranean Formations. An electric logging system using a multielectrode sonde with automatic switching in the sonde and recording the resistivity for various depths of penetration, the well being conditioned with a mud whose filtrate has a high resistivity so that a resistivity sequence of high, low and intermediate will indicate displaceable oil.

U. S. No. 2,782,365. J. H. Castel. Iss. 2/19/57. App. 4/27/50. Assign. Perforating Guns Atlas Corp.

Electrical Logging Apparatus. A casing collar locator using a pair of coils connected in an a-c bridge circuit excited from the surface, the bridge unbalance being rectified in the sonde and transmitted to the surface as d-c which is indicated.

U. S. No. 2,782,515. F. M. Mayes. Iss. 2/26/57. App. 11/3/55. Assign. Sun Oil Co.

Depth Measuring System for Wire Lines. A line measuring system having a sheave which drives a counter with a potentiometer on its shaft, the line having accurately-spaced magnetic markers which are picked up and furnish pulses that are balanced against the potentiometer voltage and any deviation used to control a motor connected to the counter through a differential gear so as to introduce the proper correction.

(See also patent 2,772,951 listed under Geochemical Prospecting; patent 2,778,947 listed under Radioactivity Prospecting; patent 2,783,449 listed under Seismic Prospecting.)

MISCELLANEOUS

U. S. No. 2,774,065. K. F. Ross. Iss. 12/11/56. App. 9/26/50.

Radio Location System. A radar system in which a sawtooth-varying signal is emitted and both the emitted signal and the reflected signal are modulated with a local oscillator and the modulation products filtered between narrow limits.

U. S. No. 2,778,013. J. E. Hawkins. Iss. 1/15/57. App. 4/10/53. Assign. Seismograph Service Corp.

Radio Surveying Apparatus. A recording system for a phase-comparison hyperbolic radio position-determining system, in which the compass heading, ship's log, and time signals are recorded on the same chart with the indications of the phase meters.

U. S. No. 2,780,753. F. M. Mayes. Iss. 2/5/57. App. 10/18/51 and 3/16/53. Assign. Sun Oil Co.

Elevation Meter. A vehicle-transported elevation-difference meter in which a pendulum is maintained statistically perpendicular to the path and the product of path length by the force required to maintain the pendulum in its null position is integrated by a pair of scaling circuits.

U. S. No. 2,781,488. C. W. Zimmerman. P. P. Reichertz, and W. C. Skinner. Iss. 2/12/57. App. 8/27/53. Assign. Socony Mobil Oil Co., Inc.

Method and Apparatus for Measuring Fluid Saturation of Core Samples. A system for determining the saturation of a core through which a fluid is flowing by adding to the fluid a known concentration of paramagnetic material and measuring the change in magnetic susceptibility of the core.

U. S. No. 2,781,970. S. Kaufman. Iss. 2/19/57. App. 10/8/51. Assign. Shell Development Co.

Analog Computer. A computer for geophysical continuation problems having a panel with a grid of jacks supplied with voltages corresponding to observed field values and a smaller mating plug board having a sampling switch whose contactor is connected to a voltage divider with taps corresponding to grid coefficients, the taps and the plugs being synchronously swept by the switches and the output voltage measured by a counter chronograph which sums up elapsed time pulses during the time required for a sawtooth voltage generator to reach each plug-tap voltage in turn.

SELECTED LIST OF U. S. PATENTS ISSUED DURING DECEMBER OF 1956 AND JANUARY AND FEBRUARY OF 1957

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2,772,561	148	2,773,252	16	2,773,942	484
2,772,567	148	2,773,253	316	2,773,985[a]	216
2,772,570	16	2,773,384	148	2,773,991[a]	172,396
2,772,633	136	2,773,386	200	2,773,996	12,484
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2,773,120	224	2,773,648	68	2,774,065[a]	312,316
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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

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REVIEWS

REVIEWS COMMITTEE

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Advances in Geophysics, Volume III, H. E. Landsbert, Editor, Academic Press, Inc., 375 pp. $8.80.

Like its predecessors, the most recent volume of "Advances in Geophysics" is poorly named. Rather than treating all phases of geophysics in which progress has been made, it deals at length with a few selected topics, seven in all. That is the only criticism I shall make of an engrossing book.

While no effort has been made to choose subjects in exploration geophysics, five of the papers will be of immediate interest to members of this society and one more, that on Geophysical Research with Artificial Earth Satellites (S. F. Singer), will be read by those curious as to the scientific value of that much publicized moon-to-be. The seventh paper, Recent Developments in the Study of the Polarization of Sky Light (Zdenek Sekera), is fascinating but, to those unfamiliar with the field, a bit mysterious. The present reviewer can only assume that the Babinet, Brewster, and neutral points appearing on the third page of the paper are well known to those skilled in the art.

Each of the remaining papers—Arctic Ice Island Research (A. P. Crary), Subcontinental Structure on the Light of Seismological Evidence (Perry Byerly), Heat Flow 'Through the Deep Sea Floor (E. C. Bullard, A. E. Maxwell, and R. Revelle), The Interior of the Earth (J. A. Jacobs), and Subsurface Geophysical Methods in Ground-Water Hydrology (P. H. Jones and H. E. Skibitzke)—is a skillful exposition. Naturally, not all of them are equally easy to read but all are complete (the papers average more than 50 pages). If one treatment stands out, it would be the treatise of Professor Bullard et al. an account of continuing research involving an ingenious instrument and clever interpretational techniques. However, there is no paper which is not well worth reading. This book will be in the library of everyone interested in geophysics as a science as well as an exploration tool.

Franklyn K. Levin

Annotated Tables of Strength and Elastic Properties of Rocks, Rudolph G. Wuerker, published by the Petroleum Branch, A.I.M.E., Dallas, Texas, 1956, 24 pp., 50 cents.

The meager existing data on physical properties of rocks are scattered through a great variety of publications, many of them hard to find. This tabulation by Professor Wuerker of the University of Illinois represents a great deal of labor. It is the most comprehensive tabulation of similar data since the publication in 1942 of the "Hand Book of Physical Constants," edited by Francis Birch.

The U. S. Bureau of Mines and the U. S. Bureau of Reclamation are the most important sources of the information tabulated. Since the interest of these organizations is primarily in rocks as engineer-

ing materials, much of the data may not be of direct interest to geophysicists. Very few measurements have been made on rocks under conditions simulating those existing in the earth. Nevertheless, this compilation should be included in all geophysical and geological libraries.

The tables list some 21 physical properties of rocks, not all of which are independent. Only a few have been determined for any one rock.

In addition to the tables, the brochure contains a bibliography of 75 entries and 10 pages of very interesting and informative notes by the author.

The brochure is not a finished publication. It was reproduced by the photo-offset process from typewritten and hand lettered manuscript. If published in finishied form, its cost would be many times the present price of 50 cents, which does not at all indicate its value and usefulness.

W. T. Born

Elasticity, Fracture and Flow, J. C. Jaeger, John Wiley and Sons, Inc., 152 pp. $2.50.

In writing "Elasticity, Fracture and Flow," Professor Jaeger's avowed purpose was "to set out, in as elementary form as possible, the basic mathematics of the theories of elasticity, plasticity, viscosity, and rheology, together with a discussion of the properties of the materials involved and the way in which they are idealized to form a basis for the mathematical theory." He has succeeded notably.

Here in a few pages are stated clearly and concisely those fundamentals which describe the elastic behavior of real materials in the bulk. There's not a thin shell calculation in the book. Professor Jaeger's intended audience was engineers and geologists; he might have added geophysicists. This is an ideal source book for anyone with only a casual interest in theoretical seismology.

In writing for a mathematically unsophisticated reader, the author has had to forego the simplification that tensor analysis or dyadics bring. Nonetheless, the choice of subjects is such that many larger texts are less useful. Particularly unusual are the sections on the Mohr representation, theory of fracture and yield criteria.

"Elasticity, Fracture and Flow," the latest of the Methuen's monographs on Physical Subjects, is one of the best of that excellent series.

FRANKLYN K. LEVIN

National Petroleum Bibliography, Issued by-monthly by *National Petroleum Bibliography*, Box 3586, Amarillo Texas, $35.00 per year.

The National Petroleum Bibliography is a new publishing venture, the first issue being that of January, 1957. It is a comprehensive index of current literature and data pertinent to all phases of the oil industry.

Some 400 publications, predominently technical and trade journals, are indexed. The Uren decimal system of classification is used because this system is already widely employed by oil companies in filing technical data.

Oil company librarians will find this new publication very valuable. Geologists and geophysicists who are interested only in their own specialties may consider the cost of the service too high, since their fields are already well covered by the "Geophysical Abstracts" of the U. S. Geological Survey, and the "Geological Abstracts" of the American Geological Institute. Executives and others whose duties encompass several phases of the oil industries should find the publication a useful one to keep on hand.

W. T. Born

World Petroleum, January 1957 issue, published by *World Petroleum*, 604 Fifth Avenue, New York, $1.00 single copy.

Almost the entire January 1957 issue of World Petroleum is devoted to material of great interest to exploration geophysicists. The lead article, entitled "Search for Big Oil" is a concise but comprehensive account of current exploration activities in all parts of the world. An article on "Oil and

Oceanography" by Dr. T. F. Gaskell of the British Petroleum Company gives an interesting account of oceanographic work with which he was connected.

Other articles discuss the weight dropping technique of seismic surveying; the new "Sonoprobe" system recently developed by the Magnolia Petroleum Corporation for obtaining detailed seismic reflection data immediately below the sea floor; and the field techniques of off-shore gravity surveying.

A series of related articles describe new tools for the geophysicist. These papers are profusely illustrated and describe in considerable detail the data processing systems developed by the following companies:

Texas Instruments, Inc.
Seismograph Service Corporation
Southwestern Industrial Electronics Company
Carter Oil Company
General Geophysical Company
The Gulf Research and Development Company

Although each of these articles was written by an engineer of the company whose equipment is described, they are entirely factual with no flavor of advertising.

Briefly described are a large number of other new or recently improved instruments including oscillographs, magnetometers, optical analogue computers, and remote-control gravity meters.

Much of the information contained in this issue of World Oil has been published elsewhere, in trade journals and advertising brochures. By collecting it and publishing it in a very attractive form the editors of World Oil have made it convenient for all interested in exploration geophysics to get a comprehensive picture of current activity in the field.

W. T. Born

PUBLICATIONS RECEIVED

American Journal of Science, v. 255, nos. 2, 3 & 4 (Feb., March & April, 1957)
Bulletin of the Earthquake Research Institute, Tokyo University, v. 34, part 4 (December, 1956)
Bulletin of the Seismological Society of America, v. 47, n. 1 (January, 1957)
Bulletin of the Chinese Association for the Advancement of Science, v. 4, nos. 2, 3, 4, & 5 (Aug., Sept., Oct. & Nov., 1956)
Deutsche Geodätische Kommission, v. 14, n. 11 (1956); v. 27, n. 13 (1956)
Deutsche Hydrographische Zeitschrift, v. 9, n. 4 (1956)
Economic Geology, v. 52, n. 1 (Jan. & Feb., 1957)
Erdol und Kohle, v. 9, n. 12 (December, 1956); v. 10, nos. 1 & 2 (Jan. & Feb., 1957)
Geofizikai Kozlemenyek, v. 5, n. 3 (1956)
Geological Abstracts, v. 5, n. 1 (March, 1957)
The Geology of Greece, v. 4, n. 1 (1956)
Geophysical Abstracts, v. 167 (Oct. & Dec., 1956)
Geophysical Digest (Calcutta), v. 2, n. 3–4 (July-Oct., 1956); v. 3, n. 1–2 (Jan.-April, 1957)
Geophysical Prospecting, v. 5, n. 1 (March, 1957)
GeoTimes, v. 1, nos. 1–10 (July, 1956 through April, 1957)
Gerlands Beiträge Zur Geophysik, v. 65, n. 4 (1956)
Journal Academy Science USSR, Series Geophysical, n. 12 (1956)
Journal of the American Society of Safety Engineers, v. 2, n. 1 (February, 1957)
Journal of Geophysical Research, v. 61, n. 4 (Dec., 1956); v. 62, n. 1 (March, 1957)
Journal of Petroleum Technology, v. 9, n. 2 (February, 1957)
Mining Engineering, v. 9, nos. 2 & 3 (Feb. & March, 1957)
Proceedings of the Cambridge Philosophical Society, v. 53, part 1 (January, 1957)
Quarterly Journal of the Geological Society of London, v. 112, n. 447 (1956)
The Review of Scientific Instruments, v. 28, nos. 1, 2 & 3 (Jan., Feb. & March, 1957)
Reports of Department of National Development, Bureau of Mineral Resources, Geology & Geophysics. Commonwealth of Australia, nos. 14, 19, 21, 27, 30 & 32
Rocznik, v. 24, n. 4 (1956)
Science, v. 125, nos. 3240–3250 (Feb. 1, through April 16, 1957)
Scientific Monthly, v. 84, nos. 3 & 4 (March & April, 1957)
Soviet Physics JETP, v. 3, n. 6 (Jan., 1957); v. 4, nos. 1 & 2 (Feb. & March, 1957)
Tellus, v. 8, n. 4 (November, 1956)
Transactions American Geophysical Union, v. 38, n. 1 (February, 1957)

MEMORIALS

STEWART BARCLAY

Stewart Barclay died of a heart attack on June 21, 1956. "Stew" suffered an attack of severe pain after breakfast and passed away before the doctor arrived. Burial was at Forest Park cemetery, Houston, Texas.

Born at Conroe, Texas, on September 8, 1912, Stew was the only child of John and Edith Barclay. The family moved to Oakdale, Louisiana in 1915 where he lived until 1932.

He entered Louisiana State University at Baton Rouge, Louisiana in 1931, graduating with the degree of Bachelor of Science in geology in 1934. He enrolled in the graduate school of geology at L.S.U. that year. In 1935 , because of severe attacks of asthma, Stew transferred to the New Mexico School of Mines at Socorro, New Mexico and in 1936 he graduated with the degree of Master of Science in geology.

Stew was first employed by Seismic Explorations Incorporated in 1936 on a field seismograph crew. In May 1937 he was employed by Phillips Petroleum Company as a computer and subsequently was promoted to party chief.

He was one of the first employees of Phillips Petroleum Company in Venezuela, transferring from the parent company to become chief geophysicist in Caracas in December, 1944. Later he also became assistant administrator of the exploration department and held these positions until January 1949. At that time he returned to the States for reasons of health.

In 1949 he resigned from Phillips Petroleum Company to become chief geologist of the Mexican American Independent Company and was located in Mexico City until 1951, when he left to become

chief geologist and assistant to the manager of exploration of the Tennessee Gas Transmission Company in Houston, Texas. He continued in this employment until his death.

Stew was a member of Oakdale Lodge, A.F. & A.M. Oakdale, Louisiana and the Houston Club, Houston, Texas. His professional affiliations included the Society of Exploration Geophysicists, the Houston Chapter of SEG, The American Association of Petroleum Geologists and the Houston Geological Society.

In May, 1942, Stew was married to Miss Mae Schienuk of Baton Rouge, Louisiana. Over the years they made a host of friends in the United States, Mexico and Venezuela. He had an admirably intelligent capacity for grasping professional problems. He was an accomplished amateur photographer, specializing in candid shots flavored with a charitable sense of good taste.

Stew's friendliness and ready sense of humor were all the more appreciated by his intimate friends, because these qualities persisted despite a severe bronchial asthmatic condition that plagued him during his life. His jovial character concealed the chronic nature of his ailment from many of his friends.

Stew is survived by his wife, Mae, young son, John, and his mother. All his many friends, both national and foreign, deeply lament his passing.

W. H. COURTIER

BARTLESVILLE, OKLAHOMA

EUGENE PERRY EVANS

On December 8, 1956, Eugene Perry Evans died suddenly of a heart attack. He was at his home in Houston, Texas when he was fatally stricken.

Gene, as he was called by his many friends, was very well known, not only in the geophysical field, but also in many civic and fraternal organizations such as the Shriners.

Born December 2, 1904, in Nooksack, Washington, Gene moved to Oklahoma when still a young lad, and grew up in the country of the Indians. During this process of growing up he became interested in geology and chose Oklahoma University as the school in which to complete his education. It was necessary for Gene to work during the summers and this he did on seismic crews for The Geophysical Research Corporation. During a part of this time the crew was stationed in Gilmer, Texas, and Gene met and later married Mildred Quin.

After leaving the University of Oklahoma, Gene continued his work in geophysics with G.R.C. until 1941, at which time he was party chief on one of their seismic crews. During this time many men were trained under the guidance of Gene.

Upon leaving G.R.C., Gene tried his hand as an independent, but soon came back to geophysics and a life of travel. During the late 1940's, while with McCollum Exploration Co., he spent quite a bit of time in Canada. In 1950 Gene became associated with Tidelands Exploration Co. as a supervisor, and remained in that position until his death.

During his geophysical career, Gene was stationed in all parts of the country and made friends with everyone with whom he came in contact, bridging easily all differences in customs and speech.

Gene is survived by his widow, Mildred Quin Evans, and two sons, Thomas Eugene, age 23, and Gerald Quin, age 19.

He is missed by his many friends and associates.

J. B. FERGUSON

HOUSTON, TEXAS
March 27, 1957

GEORGE BAILEY STONE

George Bailey Stone died suddenly of a heart attack on the morning of January 26, 1957 at his camp on Vineyard Lake in Matagorda County, Texas. The attack occurred as he arose early to prepare for a fishing trip to Caney Creek with some of his business associates. George loved the outdoors and was an avid hunter and fisherman. His untimely death is mourned by all who knew him.

George was born July 8, 1901 in Spencer, West Virginia and moved to Houston in 1906. He attended the old Central High School in Houston. His higher education was received at Southwestern University, Cornell and Colgate University. He received his Bachelor of Science degree at Colgate with a major in geology in 1925. He was initiated into the Beta Theta chapter of the Alpha Tau Omega social fraternity while at Cornell.

Upon leaving school, George entered business for himself—acquiring leases and drilling wells. On August 12, 1927 he married Dorothy Jim Manes in Austin, Texas. In 1931 he was employed by the Independent Exploration Company and spent the next ten years with field crews in the Rocky Mountain and Gulf Coast regions.

In 1941, George entered the service of his country as a technician in the Naval Ordnance Laboratory in Washington, D. C., and remained there until 1944. Upon leaving his work in Washington, he was employed by Phillips Petroleum Company in Houston, Texas as a senior geologist. With his geophysical experience he spent much of his time reviewing seismic data and working it into subsurface information. At the time of his death he was resident geophysicist and geologist for Phillips in Houston.

George was a member of the Society of Exploration Geophysicists and The American Association of Petroleum Geologists and their local affiliated societies in Houston. He was very interested in

training younger men in the value of combining subsurface geology and geophysics in the search for oil and gas.

He was an active member of the Saint Philip Presbyterian Church. His survivors are his wife, Dorothy Jim and a son Michael who is a freshman at Davidson College, North Carolina.

HARRIS H. ALLEN

HOUSTON, TEXAS
April 8, 1957

CONTRIBUTORS

Bailey Drake Frische Gates

LESLIE F. BAILEY, a native of Michigan, received the B.A. degree in geology from the University of Michigan in 1934. After completion of army service he returned to the University of Michigan for graduate work in geology and geophysics. In 1948 he joined the staff of the division of geophysics of the U. S. Coast and Geodetic Survey in Washington, D. C., where he has been engaged in geophysical research.

CHARLES L. DRAKE studied geological engineering at Princeton University and geology and geophysics at Columbia University. During 1953–1955 he served as lecturer in geology at Columbia University. He has been associated with Lamont Geological Observatory since 1948 doing research in marine geology and geophysics.

RICHARD H. FRISCHE received the A.B. degree from Miami University, Oxford, Ohio, in 1954 and an M.S. in earth science, with a major in geophysics, from New Mexico Institute of Mining and Technology in 1956. At present he is working toward a Ph.D. in earth science at New Mexico Institute of Mining and Technology, while employed as a part-time research assistant under the direction of Professor Victor Vacquier. In September, 1957, he will enter the California Institute of Technology to complete his studies in the Institute's division of geological sciences. He has been awarded a tuition scholarship and a part-time research assistantship.

JOHN P. GATES was born in Santa Monica, California, in August 1917. His training in geology at the University of California at Los Angeles was interrupted by World War II, in which he served as a naval aviator. He retains the commission of Lieutenant Commander in the Naval Reserve. After the war he returned to U.C.L.A. and received his A.B. degree in geology in 1946. Upon graduation he worked a short period in Wyoming as a geophysicist in gravity exploration, and then was employed by the Gulf Research and Development Company. From 1946 until 1949 he worked on seismic projects at the Gulf Research Laboratory and in the field. In 1949 he left Gulf to work as an engineering geologist in southern California. This work included soil tests, water surveys, oil field subsidence countermeasures in the Long Beach area, and design of utilities, roadways, bridges, and storm drains. In 1954 he rejoined the Gulf Corporation to work for Western Gulf Oil Company on the California offshore program. He is now area geophysicist for the Ventura and Santa Maria basins.

He is a member of the Society of Exploration Geophysicists and The American Association of Petroleum Geologists.

Karr Kintzinger Loomer Melton

CHARLES R. HOLMES received his B.S. degree in 1947 and the M.S. degree in geophysics in 1950, both from St. Louis University. From 1950 through 1952, and again from 1954 through 1956 he was engaged in research and teaching at the New Mexico Institute of Mining and Technology, Socorro, New Mexico. The years 1952 to 1954 were spent in study and research at The Pennsylvania State University. He is now on leave from his current position with the Atomic Energy Commission in Denver, Colorado and is fulfilling the requirements for the Ph.D. in geophysics at the Pennsylvania State University.

He is a member of the Society of Exploration Geophysicists and Sigma Xi.

PHILIP R. KARR is a native of Newark, New Jersey. He has a Ph.D. in physics from Catholic University of America, and three lesser degrees. He has taught graduate courses at Maryland University and at the National Bureau of Standards Graduate School.

Dr. Karr has been a physicist at the National Bureau of Standards and the closely associated Diamond Ordnance Fuze Laboratories for fifteen years. He has experience in noise theory, statistical communication theory, circuit theory, electromagnetic theory, proximity fuzes, gamma-ray diffusion and applied mathematics. Since October 1956, he has been a member of the technical staff of the control systems division of The Ramo-Wooldridge Corporation, Los Angeles, California, applying noise theory and related concepts to certain problems in the infrared and radar fields.

Dr. Karr is a member of the Washington Academy of Sciences, Sigma Xi, and various other professional societies. He is the recipient of a Certificate of Achievement and a cash award from the Diamond Ordnance Fuze Laboratories.

PAUL R. KINTZINGER was born in Dubuque, Iowa in 1927. He received an A.B. degree in physics from Harvard University and an M.S. degree in physics from Yale University. During 1950 and 1951 he was employed by the New Mexico Institute of Mining and Technology where he continued part time graduate work. From March 1952 until August 1953, he was employed by Newmont Exploration Limited, as party chief in charge of some electrical geophysical surveys. In September 1953, he returned to the New Mexico Institute of Mining and Technology where he continued graduate studies and worked on electrical geophysical problems with special reference to ground water. He received the Ph.D. degree in earth science in June, 1956, from the New Mexico Institute of Mining and Technology. Dr. Kintzinger is now working for the United Nations Educational Scientific and Cultural Organization and he has been assigned to the Desert Institute in Mataria, Egypt, as head of the geophysical department. He is a member of the Egyptian ground water committee.

Dr. Kintzinger is a member of the American Geophysical Union, a junior member of the American Institute of Mining and Metallurgical Engineers, and an associate member of the Society of Exploration Geophysicists.

Nafe Ritzmann Van Siclen Vacquier

E. I. LOOMER served in the Royal Canadian Air Force from 1940–1945, and attended McGill University, Montreal, from 1945–1951, graduating with the degrees of B.Sc. and M.Sc. Mr. Loomer has been a geophysicist with the Dominion Observatory since 1951. During 1951–1952 he was in charge of the magnetic observatory at Resolute, N.W.T., and is now engaged in IGY activities. He has collaborated in the publication of a number of papers dealing with transient magnetic disturbance.

BEN S. MELTON was born in Dallas, Texas, on January 2, 1904. He received the B.S. degree in electrical engineering from The Rice Institute in 1925. Following a student engineering course at the General Electric Co. and a short time as engineer with the Gulf States Utilities Co. at Port Arthur and Beaumont, Texas, he was employed by the General Exploration Co. of Houston, Texas, to do research and development work in electromagnetic prospecting for oil, during the years 1928 to 1930. Late in 1930 he entered the field of seismograph prospecting with Geophysical Service Inc., of Dallas, Texas, and except for a short period remained in that work until 1942, becoming associated with the National Geophysical Co. from 1937 until April, 1942.

In 1942 Mr. Melton joined the staff of the Applied Physics Laboratory of The Johns Hopkins University as a radio engineer on the proximity-fuze project. Following assignment to several associated projects, he entered the research program on supersonic aerodynamics, initiated toward the close of the war. In December 1948 he accepted an appointment with the Department of the Air Force and is now attached to the 1009th Special Weapons Squadron, Washington, D. C.

Mr. Melton is a member of the Society of Exploration Geophysicists, the American Geophysical Union, the Eastern Section, Seismological Society of America, the Institute of Radio Engineers, and the Philosophical Society of Washington. He is a registered professional engineer in Texas and Washington, D. C.

JOHN E. NAFE received the degree of Ph.D. in physics from Columbia University in 1948. He has taught at the U. S. Naval Academy, University of Minnesota, and Columbia University where he is now an adjunct associate professor of geology.

He has worked in the fields of molecular beams, and underwater sound, and is now engaged in research in marine geophysics at Lamont Geological Observatory.

He is a member of the Seismological Society of America, the Geological Society of America, and the American Physical Society.

O. F. RITZMANN received a B.S. degree in electrochemical engineering from Pennsylvania State University in 1922, M.S. in physics in 1924, and continued his graduate studies at California Institute of Technology and University of Pittsburgh. He taught college physics at Penn State, California Institute of Technology, Michigan College of Mines, and Lehigh University, and in 1929 joined the staff of the geophysics division, Gulf Research & Development Company. In 1944 he was transferred

von Buttlar

Whitham

to Gulf Oil Corporation as patent engineer in the patent department then located in Washington, D. C., but now in Pittsburgh, Pennsylvania. He is a registered patent agent.

Mr. Ritzmann for the past 15 years has prepared the patent abstracts which are a regular feature of GEOPHYSICS, and for this service he was awarded a life membership in SEG in 1954. He is also a member of Phi Kappa Phi, Sigma Xi, American Physical Society, American Association for the Advancement of Science, American Geophysical Union, Philosophical Society of Washington, and Physical Society of Pittsburgh.

DEWITT C. VAN SICLEN received degrees in geology from Princeton University (B.A. in 1940, M.A. in 1947, and Ph.D. in 1951) and the University of Illinois (M.S. in 1941). He has worked as an oil and gas geologist since his undergraduate days, with time out for study and military duty. Since 1952 he has done mostly research and special problems with Pan American Petroleum Corporation and a predecessor company in Houston, Texas. Van Siclen served for more than five years as an Air Force officer, chiefly at administration of technical and scientific activities, most recently in 1952 as executive officer of the Office of Scientific Research of the Air Research and Development Command in Baltimore. He has done part-time teaching at Illinois and Rutgers, and is a lecturer at the University of Houston evening school where he occasionally teaches structural geology, and reservoir geology. His major technical interest is in the application of physical principles to understanding sediment transportation and deposition, deformation, geophysical interpretation, and behavior of subsurface fluids.

He has been a member of the SEG since 1947, is a member of the AAPG, Society of Petroleum Engineers of AIME, American Geophysical Union, and other professional, civic and scholastic societies.

VICTOR VACQUIER received a B.S. degree in electrical engineering in 1927 and an M.A. degree in physics in 1928, from the University of Wisconsin. From 1927 to 1930 he was assistant instructor of physics at the University of Wisconsin. In 1930 he joined the staff of the Gulf Research and Development Co. There he worked on various aspects of magnetic prospecting and geomagnetism, including their application to military problems, the latter being conducted under the auspices of the National Defense Research Committee from 1940 to 1942. In 1942 he was transferred to the Airborne Instruments Laboratory, Columbia University, where his work on magnetic detection of submarines was being developed intensively for the Navy. At the conclusion of this activity in 1944, he joined the Sperry Gyroscope Co., where from 1945 to 1953 he was in charge of the marine instruments laboratory, whose principal task was the development of navigation, stabilization, and control devices for ships. During the latter part of that period he was also a research associate in geology at Columbia University, where he functioned largely as thesis professor. In 1953, in order to devote his efforts exclusively to geophysics, he became principal geophysicist and professor of geophysics at New Mexico

Institute of Mining and Technology, the post he holds at present. For over 3 years he has been conducting research on electrical methods for locating ground water. He was president of the section of terrestrial magnetism of the American Geophysical Union from 1954 to 1956, and associate editor of GEOPHYSICS from 1953 to 1955.

HARO VON BUTTLAR, a native of Germany, was awarded his doctorate in physics from the University of Göttingen in 1952. He received a Rotary Foundation Fellowship for the following year and went to the Institute of Nuclear Studies, Chicago, Illinois, to work as a research associate in the low-level radioactivity laboratory directed by Dr. W. F. Libby. In 1953 he took charge of the tritium project then under way.

In 1954 he accepted a position on the staff of the New Mexico Institute of Mining and Technology, where he serves presently as associate professor of physics and as research physicist in the Institute's research and development division. He is a member of the American Association for the Advancement of Science.

KENNETH WHITHAM was born in England and graduated from Cambridge University in 1948. He was awarded a Goldsmiths' Company Travelling Scholarship at the University of Toronto from 1948–1950, and received a Ph.D. for graduate work in the radioactivity of rocks in 1951. From 1951–1955 he was one of a small group engaged in the development and proving of the three component airborne magnetometer of the Dominion Observatory, and in the design of electrical magnetometers. He has taken part in aeromagnetic surveys in the Arctic and over the Atlantic. Since 1955, Dr. Whitham has been engaged in helping organize the Canadian IGY program in geomagnetism. He has published technical papers on the radioactivity of geological formations, the measurement of radioactivity, transient magnetic disturbance and airborne magnetometers.

He is a member of the Canadian National Committee for the IGY, and of the Canadian Association of Physicists.

For the biography of L. L. Nettleton see GEOPHYSICS, v. 22, p. 474.

SOCIETY ROUND TABLE

COMMITTEES FOR THE YEAR ENDING IN NOVEMBER, 1957

EXECUTIVE COMMITTEE

President: ROY F. BENNETT, Sohio Petroleum Co., Oklahoma City, Oklahoma
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Chartered February 2, 1948
W. M. Erdahl, *pres.*
John J. Rupnik, *1st v-pres.*
James F. Johnson, *2nd v-pres.*
John E. Bondurant, *treas.*
V. L. Jones, *editor*
Ralph D. Lynn, *secty.* The Carter Oil Company, Box 801, Tulsa 2, Oklahoma
Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, room 224, Petroleum Science Hall

SEG Houston Section

Chartered February 14, 1948
W. B. Lee, Jr., *pres.*
Otis B. Hocker, *1st v-pres.*
Curtis P. Harkins, *2nd v-pres.*
J. D. Watzlavik, *treas.*
Ben R. Howard, *secty.* Warren Petroleum Corp., 801 1st City Nat'l Bank Bldg., Houston 2, Texas
Meetings: Monthly, Noon luncheon ($1.65), Rice Hotel

Pacific Coast Section SEG

Chartered April 12, 1948
Flint H. Agee, *pres.*
C. A. Bengston, *v-pres., N.D.*
Lawrence S. Morrison, *v-pres., S.D.*
John A. Hugus, *secty.* Western Gulf Oil Co., 900 Wilshire Blvd., Los Angeles 17, Calif.
Meetings: Monthly, 2nd Thursday, Noon luncheon ($2.00), Biltmore Hotel, Los Angeles

Dallas Geophysical Society

Chartered August 7, 1948
R. E. Rettger, *pres.*
Chester Donnally, *1st v-pres.*
A. W. Musgrave, *2nd v-pres.*
Wm. C. Wooley, *secty.* Magnolia Petroleum Co., Box 900, Dallas, Texas
Meetings: Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Building, Southern Methodist University

Fort Worth Geophysical Society

Chartered August 7, 1948
A. E. McKay, *pres.*
R. C. Herron, *v-pres.*
V. S. Balderson, *secty.* The Pure Oil Co., Box 2107, Fort Worth, Texas

Meetings: Monthly, 4th Monday, Noon luncheon ($1.50), Texas Hotel

Ark-La-Tex Geophysical Society

Chartered March 12, 1949
Herbert J. Ferber, *pres.*
Charles P. Bragg, *v-pres.*
H. L. Grant, *secty.* Western Geophysical Company, 980 Jordan Street, Shreveport, Louisiana
Meetings: Monthly, last Monday, Noon luncheon ($1.50), Captain Shreve Hotel, Shreveport

Permian Basin Geophysical Society

Chartered January 30, 1950
R. M. Pinson, *pres.*
B. F. Owings, *1st v-pres.*
E. E. Fickinger, *2nd v-pres.*
B. A. Heidt, *treas.*
J. E. Clark, *secty.* Box 1018, Midland, Texas
Meetings: Monthly, 2nd Tuesday 7:30 P.M., free coffee & donuts, Midland Women's Club, Midland, Texas

Denver Geophysical Society

Chartered May 19, 1950
C. L. Barker, *pres.*
R. C. Kendall, *v-pres.*
R. R. Parks, *secty.* Champlin Oil & Refining Co., 333 Logan Street, Denver, Colorado
Meetings: Monthly, 1st Monday, 5:30 P.M., meeting only. Petroleum Club, Denver

Canadian SEG

Chartered January 24, 1952
George J. Blundun, *pres.*
John Fuller, *v-pres.*
Lorne H. Reed, *secty.* Universal Seismic Surveys, Ltd., 223 14th St. N.W., Calgary, Alberta
Meetings: Monthly, no set schedule

Geophysical Society of Oklahoma City

Chartered September 30, 1952
John Bemrose, *pres.*
W. B. Robinson, *1st v-pres.*
D. D. Moore, *2nd v-pres.*
Ben W. Smith, *treas.*
George E. Anderson, *secty.* Stanolind Oil & Gas Co., Box 1654, Oklahoma City, Oklahoma
Meetings: Monthly, 2nd or 3rd Monday. Time and place to be announced

Casper Geophysical Society

Chartered May 23, 1953
Dupree McGrady, *v-pres.*
R. L. Billings, *secty.* Forest Oil Corp., 254 N. Center St., Casper, Wyoming
Meetings: Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming

Geophysical Society of South Texas

Chartered November 9, 1953
Wm. R. Gray, *pres.*
Wm. Harry Mayne, *v-pres.*
Jack W. E. Edmonson, *secty-treas.* 713 First Nat'l Bank Bldg., San Antonio 5, Texas
Meetings: 1st and 3rd Wednesdays, Noon luncheon, Sommers Cafeteria, Main Plaza, San Antonio

Southeastern Geophysical Society

Chartered April 1, 1954
Merrill Smith, *pres.*
R. E. Sheriff, *v-pres.*
G. F. Berry, *secty.* 204 Carondelet Bldg., New Orleans, Louisiana
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans

Montana Geophysical Society

Chartered April 12, 1954
Jack W. Peters, *pres.*
C. F. Moore, Jr., *1st v-pres.*
Gordon Cloepfil, *2nd v-pres.*
Ward T. Langstroth, *secty-treas.* The Carter Oil Co., Box 1982. Billings, Montana
Meetings: Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club

Jackson Geophysical Society

Chartered May 12, 1955
Fred Forward, *pres.*
W. J. Robinson, *v-pres.*
R. Long, *secty.* Stanolind Oil & Gas Co., 1166 Raymond Road, Jackson, Mississippi
Meetings: Monthly, during 3rd week, 5:30 P.M., refreshments, 6:30 P.M., dinner ($2.00), Roof Garden of Robert E. Lee Hotel, Jackson, Mississippi

Southwest Louisiana Geophysical Society

Chartered January 4, 1956
John W. Bell, Jr., *pres.*
A. V. Hargis, *1st v-pres.*
W. W. Daly, *2nd v-pres.*
Lawrence N. Ott, *secty.* Tidewater Oil Co., Box 1147, OCS, Lafayette, Louisiana
Meetings: to be announced

Utah Geophysical Society

Chartered October 29, 1956
T. E. Hobbs, *pres.*
J. R. Cheney, *1st v-pres.*
K. L. Cook, *2nd v-pres.*
John W. Erwin, *secty.* 600 Crandall Bldg., Salt Lake City 1, Utah

Dakota Geophysical Society

To be chartered
W. E. Phillips, *pres.*
Hugh McCain, *1st v-pres.*
Quin Hayes, *2nd v-pres.*
R. R. Phair, *secty.* Roundup Powder Company, Box 432, Bismarck, North Dakota
Meetings: Monthly, 1st Friday, 7:30 P.M., Petroleum Club, Prince Hotel, Bismarck, North Dakota

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists

John M. Perrigo, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado
Meetings: to be announced

Geophysical Society of Saint Louis University

Thomas McEvilly, *secty.* Saint Louis University, 3621 Olive Street, St. Louis 8, Missouri
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology

SEG Houston Student Section

James A. Sherar, *secty.* 3618 Overbrook, Houston, Texas
Meetings: to be announced

University of Toronto Geophysical Society

John E. Hogg, *secty.* 49 St. George Street, Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursdays, 4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society

Vernon Malahy, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section

John T. Sample, Jr., *secty.* Box 56, Texas Western College, El Paso, Texas
Meetings: to be announced

Pennsylvania State University Geophysical Society

James B. Imswiler, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society

Howard L. Confer, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday, Noon, Mines Building. Other special meetings to be announced

Georgia Institute of Technology Geophysical Society

William Hogarth, *secty.* Box 4748, Atlanta, Georgia
Meetings: to be announced

A & M College of Texas Student Geophysical Society

Robert T. Smith, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

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MEETINGS

ABSTRACTS OF PAPERS PRESENTED AT THE ELEVENTH MEETING OF THE EUROPEAN ASSOCIATION OF EXPLORATION GEOPHYSICISTS

Some Magnetic Anomalies in Belgium

EDMOND HOGE†

The author presents an unpublished chart of the vertical intensities of the earth's magnetic field, established for the southeastern part of Belgium.

This chart brings into evidence:

1. A large regional anomaly covering all the Ardennen.
2. More located anomalies where metamorphic rocks are present (Hautes-Fagnes and regional of Paliseul, Libramont and Bastogne).

More detailed surveys have been undertaken in these regions and the author deals with the connection between magnetic anomalies and geology.

† Royal Meteorological Institute of Belgium, Department of Terrestrial Magnetism and Electricity.

The Behavior of Worden Gravity Meters Used by the Italian Karakorum Expedition (1954–55) under Periodic Variations of Ambient Temperature and under Rapid Variations of Ambient Pressure

MICHELE CAPUTO†

A Worden gravity meter has been subjected to an ambient temperature which varies sinusoidally with respect to time, for the purpose of determining simultaneously the corresponding variations of temperature in the interior of the Dewar vacuum bottle and the variations in readings of the gravity meter.

In a corresponding study, a second Worden gravity meter has been studied with respect to rapid variations of ambient pressure.

† Istituto di Geodesia e Topografia, Universita, Trieste.

Correlation of Rock Density Determinations for Gravity Survey Interpretation

J. T. WHETTON, J. O. MYERS, AND R. SMITH†

INTRODUCTION

For the reliable interpretation of a gravity anomaly map, it is necessary to know as accurately as possible the density of the rocks beneath the surveyed area in order to establish the horizons of maximum density contrast. In a local survey done over a portion of the concealed coalfield of York-

shire (northern England), it was necessary to utilize several methods of rock density determination in order to assess the density changes in the range of strata involved. The different methods have, where convenient, been made to overlap and a correlation between them is thus possible and yields interesting results. Work on such correlations has been published by Hammer and Parasnis, but their results disagree with each other to some extent. This paper, it is hoped, makes a further useful contribution to the problem.

METHODS EMPLOYED

The standard laboratory and field methods have been used to cover a series of beds which incorporates the following lithologic types:

1. A poorly cemented ferruginous sandstone; the Bunter sandstone of the Vale of York.
2. Marl beds often with gypsum and anhydrite; the upper and middle Permian marls of the Yorkshire Permian succession.
3. Magnesian limestone beds varying from massive to flaggy; the upper and lower magnesian limestone of the Yorkshire Permian succession.
4. A series of coal measure beds consisting of alternations of sandstones, siltstones, mudstones and shales in which individual beds rarely attain a thickness of more than 40 ft.

The methods used can be sub-divided into four groups for purposes of correlation:

A. Laboratory measurements on rock samples from quarries and coal mines.

B. Laboratory measurements on rock samples from boreholes.

C. Density determinations from hill surveys.

D. Density determinations from measuring the vertical change of gravity in mine shafts.

The laboratory method used in groups A and B is similar to that described in detail by Holmes and Moore. It involves the saturation of the rock sample with distilled water in vacuo.

Both wet and dry densities were found, but, with one or two exceptions, the wet density is the one considered in the correlations. The method used in section B is that due to Parasnis, which is a development of Nettleton's method. It presumes a straight line relationship between gravity anomaly and height. By keeping the density traverses short in length, it is considered that regional variations were negligible where this method was used and that hence its results are reliable. The fourth method has been described by Hammer and, more fully, by Domzalski, and is considered to be the most suitable but, unfortunately, it is not always possible to use it due to lack of facilities.

CONCLUSIONS FROM THE METHODS

1. For a series of coal measure beds as indicated above, the laboratory measurements give lower values than the shaft measurements for corresponding strata. However, if (as is usually the case for gravity interpretation) contrasts within the series and not absolute values are desired, then both sets of results are reliable within themselves.

2. For magnesian limestone strata, it is concluded from the results that weathering can alter the density of these beds appreciably. This factor has resulted in the density data obtained from hill transverses (which relates to hill formations in which the rock is more exposed to weathering agents, particularly underground water circulation) being very variable and lower in value than the more consistent results obtained by laboratory measurements on rock samples from boreholes. Measurement on rock samples from quarries also gives lower and more variable density values. Hence, to interpret correctly a gravity map covering an area where such beds outcrop, it is necessary to apply a density value increasing with distance from outcrop for those beds.

3. For more marly beds, the weathering effect is not as important and hill traverse results suggest that the values obtained by laboratory measurements are lower than the true values.

4. For poorly cemented sandstones, the results indicate that weathering is again an important factor. The hill traverse results, though consistent within themselves, are lower than those obtained from laboratory measurements. The high and constant porosity of these rocks is another factor which will reduce the reliability of the hill traversing method.

APPLICATION TO THE SURVEYED AREA

From the results of the density measurements, only those relating to the coal measures were considered to be satisfactory. The others indicated a horizontal density gradient for the Permian beds and a range of 2.0 to 2.35 grams/c.c. for the Bunter sandstone. The problem of solving the value of the density gradient and that of finding the correct density to be used for the Bunter remained, and the survey evidence was used to solve them. The surveyed area covered a section of ground that had been well explored by boreholes and hence was reasonably well-known geologically. Two intersecting sections were drawn on this borehole evidence and by using different values for the density of the Triassic within the limits determined by the density measurements, along with the computed density change for the Permian, the values which produced the best fit of observed and calculated anomalies were found. These values, which were then applied to the remainder of the survey area, resulted in a satisfactory interpretation in terms of local structures known to be present in the area, and the location of some which were previously unknown.

† Department of Mining, University of Leeds.

Charting of Depth Sections with the Help of Electronic Computers

V. Baranov and J. Tassencourt†

One calculates most frequently the depths and offsets of seismic reflectors, under the hypothesis that the propagation velocity varies linearly with respect to depth.

For a more complex velocity law the calculations (which require two integrations) become too difficult. This is the case, for example, when the velocity law is given experimentally by a continuous velocity log.

In actual practice, one generally supposes that the velocity, $V(z)$, does not depend upon the shot point position. Certainly, this is not true when the seismic ray encounters a dipping interface separating two strata of different velocities. The velocity then is a function of two variables.

These problems can be solved easily and rapidly with electronic computers having magnetic drums. After reviewing briefly the theory and the general formulas, the following problems are studied:

1. Construction of charts for any velocity law (given, for instance, by continuous logging);
2. Plotting of depth sections for the above velocity law;
3. Exact solution of the same problem when one can draw a "phantom horizon" on the time section.

A logical chart is established for each of the above problems. Of course, the coding will depend on the type of computer used.

† Compagnie Générale de Géophysique, Paris, France.

The Nature and Synthesis of the Seismic Refraction Arrival

F. W. Hales†

Some of the aspects of classical theory, as applied to seismic refraction techniques, and which are in discordance with observed facts, are outlined.

An analytical synthesis of the wavelet which progresses along the refractor after initiation by an impulsive source is made and this wavelet is thereby shown to comprise an initial shock wave followed by the true critically refracted wave. The resulting wavelet determines the nature of the signal recorded by a geophone at the surface. The derived signal is seen to agree closely in shape with observed refraction first events.

Practical implications of the treatment are discussed.

† Seismograph Service Ltd., Palermo.

Direct Recording vs. FM Recording in Seismic Tape Machines

LOUIS W. ERATH†

This paper describes the two methods of magnetic tape recording used today in the seismic industry. It discusses objectively the characteristics of both methods including historical material, discussion of circuitry, magnetic tape, drive systems, effects of flutter and harmonic distortion, signal transfer, and tape transport construction. The paper also includes discussion of noise and reproduction of transient signals.

Diagrams illustrating the two recording systems, their frequency response and phase shift characteristics, distortion and noise levels as well as typical wave forms are also attached.

† Southwestern Industrial Electronics Co.

Determination of Very Deep Reflectors by Reflection Seismograph Work

G. DOHR†

Reference should be made to Schulz who observed very deep reflections in the Nahe-Senke area in the contact zone between diorite and gabbro. A study was undertaken of very deep reflections found in some other areas during normal reflection seismic surveys. Especially studied was the area in front of the Black Forest containing the Rastatt-Achern, Baden-Oos and Buhl areas having reflection times from 6.5 to 7.5 seconds and from 7.5 to 8.0 seconds. The Murnau (Oberbayern) area was also studied, this area having a reflection time from 6.5 to 11.0 seconds. For several reasons it is possible for us to state that these very deep events are not multiple reflections. The reasons are as follows:

1. The very different nature of the bedding in the upper zone reflectors as compared with the deeper reflectors.
2. Absence of any correlation between the very deep reflections and the upper reflections.
3. The presence in areas of tectonically deformed strata, of an almost horizontal boundary plane lying at a great depth.

The depth computations were based on an average velocity of 4,500 meters per second (14,800 feet per second) for the Mesozoic, and velocities from 5,500 to 6,000 meters per second (18,000 to 19,800 feet per second) for the Paleozoic and crystalline schists.

It was possible in some areas to correlate very deep reflections, directly by several records. However, since this correlation was possible only in a few exceptional cases, a method was employed consisting in ascertaining statistically the single and very deep reflections, and representing their frequency values graphically and their distribution in space as a function of reflection times at intervals of 0.2 seconds. Thus data were obtained on the configuration of deep planes of discontinuity. This procedure was reapplied on the Nahe-Senke area and gave results agreeing satisfactorily with those obtained by Schulz.

In the Murnau area planes of discontinuity were determined down to 18 and 30 km (6,000 and 10,000 feet) with an error probably not greater than 10 percent. The plane lying at a depth of 30 km (10,000 feet) was identified with the Mohorovicic schist.

† Seismos, Hannover, Germany.

Refraction of Seismic Waves in an Anisotropic Medium: Application of Anisotropic Principles to a Borehole in the Sahara and an Interpretation through Seismic Refraction

PHILLIP DUNOYER†

Correct interpretation of seismic refraction calls for a knowledge of velocities along slant raypaths; therefore for a knowledge of the anisotropy factor.

The anisotropy factor k is defined as the ratio of the horizontal over the vertical velocity. The anisotropy is assumed to be elliptical. From that hypothesis, one derives the relationship between angles of refraction at an interface.

Considering a borehole in which formations of different velocities and anisotropy factors occur, it is shown how to calculate the anisotropy factor for successive layers, by using radial surveys at the interfaces between the layers.

Experiments are described, which were carried out recently in a borehole in northern Sahara. The anisotropy of four layers extending from the surface down to 2,264 m (7,420 ft), has thus been evaluated.

The influence of anisotropy on the relationship between delay-time and depth as well as between delay-time and offset is then studied. Examples are chosen from the borehole considered above and a seismic refraction survey performed in that same area.

The influence of anisotropy appears to be considerable, which shows how essential the knowledge of anisotropy is to a correct interpretation of seismic refraction.

† Compagnie Française des Petroles.

Reflected Refractions Waves on a Fault

H. Meder†

The existence and interpretation of reflected refraction waves have been known for some time. This paper deals with the case of reflected refraction waves at non-horizontal key-horizons.

It is shown how to determine the position of the fault by which the refracted waves are reflected by means of a known key-horizon. This method is illustrated by an example.

† Prakla, Hannover, Germany.

Some Considerations on Well Velocity Surveys Carried Out in Italy by Agip Mineraria With Particular Reference to the Po Valley

F. Quarta and C. Maino†

The numerous well velocity measurements carried out in Italy by Agip Mineraria are considered, in an attempt to establish some correlations between the determined velocities and the stratigraphic and lithologic characteristics of the terrains on which the measurements were made.

The distribution of the seismic velocity is especially discussed in relation to depth, age, and lithologic composition of the Tertiary formations in the Po Valley.

Finally, mention is made of some satisfactory results newly obtained on the basis of such considerations, particularly for the definition of stratigraphic traps.

† Agip Mineraria, Milan, Italy.

Distribution of Seismic Energy in Stratified Media

A. Romagna Manoja†

The distribution of seismic energy in stratified media is analyzed and the influence of bent strata on the amplitude of the waves transmitted to the geophones is demonstrated. Emphasis is placed on the importance of long waves being refracted toward the surface and carrying more energy than the short waves.

† Agip Mineraria, Milan, Italy.

Seismic Model Experiments on Thin Layers

E. Carabelli and R. Folicaldi†

Two-dimensional seismic model experiments have been carried out by the Laboratory of Fondazione Lerici in the Polytechnic School of Milan.

For this research the Laboratory has projected and constructed a complete set of equipment, including pulse generators, piezoelectric transducers and amplifiers for detecting the waves propagated through the models.

We discuss herewith reflections from horizontal layers, relatively thin as compared with the wave lengths of the sound waves propagated through them.

The thickness of the layers ranged from one fiftieth of a wave length to several wave lengths. The strata consisted of materials sometimes of lower and sometimes of higher sound velocities than the homogeneous surrounding media.

The purpose of this research was to account for the simple and multiple reflections from these very thin reflecting layers and to determine the effect of variations in the thickness of the layers relative to the wave lengths involved upon the reflected energy and to determine the conditions under which the reflections appear upon the seismogram as independent events.

† Fondazione Lerici del Politecnico de Milano, Milan, Italy.

The Bottom of the Strait of Messina—Geological and Geophysical Studies

E. Beneo and R. Cassinis

In the fall of 1955, a geological and geophysical survey was carried out along the coasts and offshore in the Strait of Messina. The purpose of the exploration was to determine the possibility of indicating a bridge between the island of Sicily and the continent, namely:

1. To determine the lithologic composition of the shallow materials as well as that of the underlying metamorphic basement.
2. To measure the thickness of the sedimentary formations both below the shores and below the channel's bottom.
3. To outline the buried tectonic features and the morphology of the metamorphic basement.

These three problems, each having a certain number of unknown questions, were considered in their general sense, following the well known procedure of studying:

a. The detailed geology in the regional geology;
b. The physical characteristics of the formations (geophysics);
c. The interpretation of the records.

It was decided at first to undertake a systematic study of all the outcropping terrains on both sides of the channel; determining their nature, extension, mutual relations, maximum and minimum thickness and age.

Four geologists, particularly acquainted with Sicilian facies and tectonics, worked together for over two months on both sides of the Strait on the mainland.

The results of these studies led to a clear interpretation of the geophysical data.

The stratigraphy, thickness, facies and dislocations have been surveyed. The latter appear in the channel as a fault system, limiting the dislocated blocks.

The most ancient part of the outcropping series is represented by metamorphic formations (sedimentary-eruptive) whose thickness was considered indefinite. It was assumed that a noticeable thickness of the top of this basement consisted of altered material.

The overlying formations are mostly non-metamorphic marine sediments, generally made of clastic rocks, and corresponding to ages lying between the Neogene and the Pleistocene.

The geophysical exploration was carried out with the help of two methods: refraction and reflection seismic, and electrical resistivity.

By the seismic method the thickness of the upper formations was measured and the morphology of the bedrock was outlined. With the help of both the electrical resistivity and seismic velocity measurements it was possible to obtain the lithologic data of the formations by the comparison of the two physical parameters.

The resistivity measurements were made only along the coast; the reflection and refraction lines were laid also in the Strait, and the technique used for the offshore survey is described in particular.

The very fast and variable stream and the deep water were the main difficulties of the survey. To select the best hours of the day for operations an accurate evaluation of direction and speed of the water flow was necessary.

Special arrangements were made to locate the shot points and the cable with the geophones during the offshore operations.

To reduce the strong noise caused by the water flow and by the waves, the towing of the floating cable was done very carefully.

Lay-outs employed are described.

Another difficulty encountered was the intense traffic of ships and fishing boats.

The results of the integrated survey demonstrated that the lithologic conditions of the sediments, as well as those of the metamorphic basement, do not show noticeable lateral changes, i.e., the values of the physical parameters are the same both under the coasts and under the channel's bottom. Core wells will be drilled on both shores of the Strait; the elastic properties of such cores could be referred also to the materials underlying the channel's bottom.

Velocity and resistivity measurements were made on the outcrops of each formation also.

The shallow layer of loose material found on the shore was not found on the bottom of the Strait. The sedimentary formation on the bottom seems to consist of a rather consolidated and hard material. The metamorphic bedrock has a very thick top of altered material and the seismic velocity increases very slowly with the depth.

Reflection Seismography Work in Southwest France Leading to the Discovery of the Parentis and Mothes Oil Fields

H. L. Brewer†

Geophysical methods are needed to detect, outline and detail the structures within the exploration permit of the Esso REP in southwest France. The reflection seismograph has been found to be the most reliable method to outline and detail the structures. The use of the reflection seismograph in this area is made difficult due to the thick surface sands, a high level of ground unrest, random interferences, and a complicated subsurface. These difficulties were overcome by the use of a star pattern of geophones.

This method gave good shallow and deep reflections in the greater Parentis area and showed the presence of the Parentis and Mothes anticlinal trend which was found to be oil bearing when tested by the drill. Parentis is the largest oil field in Europe outside of the Iron Curtain. It is felt that Parentis and Mothes would not have been found without the use of pattern geophones.

† Chief geophysicist of the Esso REP on loan from The Carter Oil Company.

Accident Statistics

H. Richard†

The chairman of our safety committee has concluded that European geophysicists do not consider accident statistics seriously enough. These statistics, however, are the best means at our disposal for studying the factors influencing the number and the severity of accidents.

It seems absolutely necessary to us that two points should be stressed:

1. The accident reports must be established correctly;
2. The interpretation of each report and the interpretation of the statistical data must be done methodically.

If these conditions are fulfilled, one should be able to create, at all levels, a technical and psychological climate which will allow great improvements to be made in protecting geophysicists against accidents.

† Compagnie Générale de Géophysique, Member of the Committee on Safety of the EAEG.

Geophysical History of the Iron Mine at Forsbo, Sweden

G. TØRNQVIST†

The paper gives an example of how prospecting for iron ore is carried out in Sweden. High grade deposits of magnetite ore have been known for a long time within the leptite formation near Forsbo, but the mining has been very restricted because of the small size of the ore-bodies. A new magnetic ground survey disclosed a weak but extensive anomaly on the side of the known zone, which could be interpreted as being due to a magnetic body of a sizeable width at about 100 m (330 ft.) depth. Drilling was recommended and a workable deposit was found. Mining work has been carried out in 1955 so far that a comparison between the interpretation of the magnetic data and the ore reserves can be attempted. A short description of the procedures for determining the extension in depth of magnetic bodies, and a diagram showing the influence of topography on magnetic measurements are also included in the paper.

An electromagnetic survey was carried out within the same area, and the type of indication obtained over magnetite ore is shown.

† AB Elektrisk Malmletning.

On the Influence of Lateral Variation of Resistivity on Electrical Prospecting

L. ALFANO†

The object of this theoretical paper is to contribute in the improvement of the interpretative technique relative to vertical electrical sounding.

On such an attempt, the possibilities of calculating theoretical diagrams were studied for the case of coexisting planes of discontinuity in electrical resistivity which are parallel to the ground, and analogous discontinuity planes normal to the ground.

In the present mathematical scheme many geological configurations of practical interest are contained; i.e.: the case of a fault, or that of a sharp interruption of a layer, and generally every case where lateral variations occur in both deep and surface resistivities.

The mathematical study was necessarily carried out by adopting a rectangular coordinates system.

It is shown that when the electrical resistivity values of the different sections are such as to satisfy to some particular conditions, the computation becomes very simple and does not differ excessively from that of a horizontal set of layers.

The solution for the most general values of resistivities was also derived, but it presents, naturally, greater difficulties.

† Fondazione Lerici del Politecnico di Milano, Milan, Italy.

Seismic Refraction Survey of a Hydroelectric Plant Site in Northern Sweden

E. WELIN†

The seismic methods for determining the bedrock depth has had, during the last ten years, an ever increasing and widespreading application in Sweden, especially as a reconnaissance method for planning hydroelectric projects. This paper describes a survey carried out for a projected power plant in northern Sweden. Three alternatives for tunnel lines and dam sites were surveyed, the total length of profile investigated comprising 16 km (10 miles). Some twenty drill holes were set down through the glacial drift (depths down to 19 m (62 ft) and drilled into the bedrock, affording a good confirmation of results of the seismic work. The cost of the power station amounts to 12 million dollars of which only 12,000 dollars (1/10 of one percent) is for seismic investigations. Through this comparatively small expenditure of time and money it was possible to choose an optimum choice for tunnel line and dam site.

† AB Elektrisk Malmletning.

Application of Geophysical Prospecting to Civil Engineering Problems: Hydroelectric Development of the Rhone Valley

J. J. Breusse†

Civil engineering problems, particularly along the river dam site projects give to geophysics an interesting and rather important field of activity. Electrical prospecting, with its particular techniques of electrical sounding, and the shallow depth seismic refraction method, have been very helpful in solving the basic problems connected with the great development projects of the Rhone Valley, especially between Lyon and Orange. These methods are still the best tools for exploration before drilling. The main problems dealt with are:

1. The search for a convenient bedrock for water-plants and gates;
2. The laying out of head and tail races;
3. The study of alluvial water levels in order to determine the consequential effects of the opening of the tail races.

Two examples have been chosen among the numerous cases studied. The first example deals with the initial development zone: Donzere-Mondragon. The results of the geophysical survey have led to a new and completely different layout of the tail race and to the discovery of the St. Pierre bedrock, which has proved to be an excellent and well situated foundation site for the plant.

The development of the Montelimar zone (immediately upstream to the previous zone) is the object of the second example. After having demonstrated by a general reconnaissance with electrical soundings that the bedrock was mainly sandstone the problem was to outline carefully the soft sandstones areas so easily excavated, and to be able to avoid the hard sandstones areas in the lay out of the tail race. Seismic refraction was able to solve this problem very well, thereby avoiding a prohibitive number of drill holes. The subsequent borings gave a remarkable confirmation of the geophysical results.

Some statistical data are presented concerning the importance of the geophysical surveys for the Rhone Valley development during the last ten years.

† Compagnie Générale de Géophysique, Paris, France.

Practical Methods of Interpretation in Seismic Refraction

P. Gros† and Y. Ledoux‡

After a short historical summary about the evolution of ideas concerning technique and utilization of refraction shooting, the authors analyze comparatively the different methods actually used. Drawing especially their attention to the several ways considering the problem of interpretation, they insist on the possibilities offered by Gardner's method.

The restrictions bounding the application of this process to well defined cases (small dips, uniformity of velocities) have been partially removed by means of some modifications; several recent examples are given to support this theory, which extends to a considerable degree the field of refraction shooting.

† Compagnie Générale de Géophysique, Paris, France.
‡ Compagnia Italiana di Prospezioni.

New Criteria for Interpreting Seismic Refraction Data

C. Contini, C. Maino and M. Ranucci†

The paper is divided into the following chapters (each one consisting of 20 sections): execution of surveys; picking of seismograms; reduction of observed values; principles for geological interpretation; plane layers with constant velocity; bending strata with constant velocity.

It is the authors' opinion that the following sections are the most important for routine work:

No. 5 and 6—Reduction of observed values;
No. 8 and 9—Optics of seismic rays and diffraction;
No. 13 —Faulting of strata;
No. 16 —Treatment of emergence angles, of more general application than Gardner's method.

Also useful for a speedy and safe elaboration of the results are the tables referring to Figs. 2, 3, 4, 5, 8, 10, and 11.

Only strata with constant wave velocity are considered; the most general case of strata with variable velocity will be dealt with in a subsequent publication.

† Agip Mineraria, Milan, Italy.

AMERICAN PHYSICAL SOCIETY SOUTHWESTERN MEETING

The 1957 Southwestern Meeting of the American Physical Society was held at Norman, Oklahoma in the buildings of the University of Oklahoma on Friday and Saturday, March first and second, 1957. This was the fifth of a sequence of meetings in the southwestern area, or sixth if we include the Albuquerque meeting of 1953 and was the very first meeting ever held by the Society in the state of Oklahoma. The chairman of the local committee was Professor J. Rud Nielsen of the University of Oklahoma.

The banquet of the Society was held on Friday evening in the ballroom of the Oklahoma Memorial Union with Professor H. D. Smyth of Princeton University presiding. An after-dinner speech was delivered by Laurence H. Snyder, dean of the graduate college of the University, and presently president of the American Association for the Advancement of Science. The title of Dean Snyder's speech was "Heredity and Modern Life."

One hundred and eight authors presented a total of 120 papers of which 23 were invited papers and 97 contributed papers. These papers were given in a program of 11 sessions during the two days of the meeting. Subject matter of the 11 sessions was as follows:

(1) Solid-state physics
(1) Theoretical physics
(1) Molecules
(2) General physics
(1) Low temperature physics
(1) Fluid dynamics
(1) Nuclear physics
(2) Geophysics
(1) Electron physics

SPEAKERS AT THE SOUTHWESTERN MEETING OF THE AMERICAN PHYSICAL SOCIETY

Left to right: Victor Vacquier, V. L. (Vic) Jones, Karl K. Darrow (Secretary of the American Physical Society), J. O. Parr, Jr., William Schriever, W. M. Rust, Jr., Norman Ricker, Irwin Roman, and Raoul Vajk. All are members of SEG except Dr. Darrow.

Invited papers on the program were drawn mainly but not wholly from the southwestern area, and in accordance with the usual practice at these meetings ranged widely over physics but with a particularly large number in geophysics. Invited speakers in geophysics were N. H. Ricker, Irwin Roman, W. M. Rust, Jr., Ellis Strick, Victor Vacquier, and Raoul Vajk, and their papers were scheduled for Saturday morning and Saturday afternoon. Invited speakers in other fields of physics were J. M. Burgers, G. F. Carrier, R. R. Grilly, Max Jammer, F. A. Matsen, J. Rud Nielsen, A. W. Nolle, V. H. Regener, D. H. D. Roller, Richard Rosa, S. A. Schaaf, G. K. Teal, James Terrell, M. W. Teucher, Otto Theimer, E. J. Workman, and J. R. Zimmerman. The invited papers in geophysics were as follows:

"The Propagation of Transient Elastic Disturbances in Solid Bodies," by N. H. Ricker

"A Theoretician's Observations on the Role of Elastic Wave Propagation in Geophysical Exploration," by Ellis Strick

"Modern Techniques of Exploration Geophysics," W. M. Rust, Jr.

"Geophysical Exploration for Ground Water," by Victor Vacquier

"Gravity Prospecting," by Raoul Vajk

"Some Magnetic and Electrical Methods of Geophysical Exploration," by Irwin Roman

Contributed papers in geophysics were:

"A High Radiometric Anomaly Caused by Fallout and Its Decay," by J. O. Parr, Jr.

"Correlation of Adjacent Gravimeter Surveys," by V. L. Jones

The registration for the meeting was 273 scientists from all parts of the nation. This registration exceeded the anticipated 200.

V. L. JONES

ANNOUNCEMENTS

SEG DONATES LIBRARY TO THE UNIVERSITY OF TULSA

In 1947 the University of Tulsa Library became the official depository for SEG exchange publications (*vide* GEOPHYSICS, v. 12, p. 517). Since that time periodicals and books received from other learned societies throughout the world have been catalogued and retained by the library for the society, with provision for loan to SEG members.

In its meeting at New Orleans October 28, 1956 the executive committee voted " . . . to donate to the University of Tulsa Library all issues of publications that have been received and that will be received in the future. The library will bind these issues into volumes which will be stamped 'donated to the U. of T. Library by SEG'." The committee stipulated that these volumes would be available for loan to readers of GEOPHYSICS. The purpose of this action was to improve the usefulness of the collection to all members of the society, as well as to the faculty and students of The University of Tulsa.

Although some series are incomplete, most of the periodicals listed regularly in GEOPHYSICS under "Publications Received" are now available for loan to members of the society and regular subscribers to GEOPHYSICS. A member of any grade is welcome to visit the library, and upon presenting his membership card he will be entitled to loan privileges. Each loan is limited to two weeks, and when shipment is necessary a minimum fee of 25¢ per volume must be paid in advance to cover postage and handling. Volumes cannot be mailed outside the United States of America. Microfilm copies from publications allowing that privilege can be furnished at 5¢ per exposure with a minimum charge of 50¢ per job. Upon application for a loan a member or subscriber should advise whether or not he will accept microfilm.

Inquiries should be directed to The Librarian, The University of Tulsa, 600 South College, Tulsa, Oklahoma.

SAINT LOUIS UNIVERSITY CHAPTER SPONSORS SEG EXHIBIT

Operation Vanguard of the International Geophysical Year was featured in the SEG exhibit during the annual meeting of the American Association of Petroleum Geologists, April 1–4, 1957 in St. Louis. Commercial exhibit space was furnished SEG without charge by the AAPG. The display was built by members of the Saint Louis University SEG, a student chapter of the Society, and featured a cutaway model and a prototype of an "earth satellite" with a color-coded diagram of the three-stage rocket which will carry the satellite into its orbit. Junior and senior students in engineering geophysics at Saint Louis University's Institute of Technology were present throughout the meeting to describe the IGY project for their earth-bound cousins.

Senior students participating included Theodore G. Carr, John J. Dowling, John F. Eisenhauer, William C. Fogarty, Paul C. Heigold, John R. May, and Gilbert A. Wilhold. Juniors included James L. Murphy, William H. Reeves, George C. Thien, and William T. Valenta.

IGY WILL BRING 1,500 SCIENTISTS TO TORONTO

More than 1,500 experts in the earth sciences will gather at Toronto, September 3–14, 1957, to hold the Eleventh General Assembly of the International Union of Geodesy and Geophysics (IUGG). The main topic will be the International Geophysical Year (IGY), which starts on July first, 1957. Delegates will come from 50 countries in all parts of the world to review the IGY opening and lay final plans for the vast joint enterprise.

The International Geophysical Year, an 18-month concerted effort by more than 50 nations and 5,000 scientists, is expected to cost well over $300 million. From July 1957 to January 1959, experts in 14 fields of research will investigate the earth from pole to pole, from ocean floor to outer space. All

over the world simultaneous measurements will be taken on such phenomena as the aurora, cosmic rays, meteors, the upper atmosphere, glaciers, oceans, gravity, magnetism, earth tremors, solar flares and sunspots.

The IGY will climax the efforts of many centuries to solve mysteries of the sun and the earth, to form a unified picture of our physical environment. In human affairs it is heralded as a new promise of goodwill among nations.

Each member country of the IGY is making a specific contribution. Largest programs are those of the United States, Britain and the Commonwealth, and Soviet Russia. Several countries will employ rockets to probe the upper atmosphere. Twelve nations will explore and investigate the Antarctic. Both the United States and Russia are planning to launch man-made satellites which will encircle the earth in outer space.

Canadian scientists are playing a creditable role in the IGY, with programs operating in nearly all departments, omitting only the rocketry and satellite studies.

The arrangements committee of the International Union of Geodesy and Geophysics Eleventh Assembly in Toronto, September 3–14, pose with equipment to be used this summer by University of Toronto and Canadian Research Board expeditions in British Columbia and the Canadian Arctic to study glaciers as part of the International Geophysical Year. Professor J. T. Wilson (center), vice-president of the IUGG and chairman of the arrangements committee, holds a gravimeter for measuring gravity on Canadian IGY investigations. In front of Professor Wilson, J. A. Jacobs, secretary of the committee (left), and R. M. Farquhar, are various pieces of "seismic equipment."

The Eleventh General Assembly of the IUGG at Toronto will bring together its seven international associations, whose interests cover nearly all aspects of the IGY. The two weeks of the assembly will feature lectures and papers by some of the world's outstanding scientists.

Typical subjects to be discussed are: the age of the earth (now estimated at 4½ thousand million years); polar wandering (different locations of the tropical regions in past ages); the warming cycle (whether the earth's climate is getting warmer); measuring distances between continents by radar; the origin of cosmic rays and their immense energies; sun spots and solar flares; jet streams in the atmosphere; the true shape of the earth; magnetic storms and radio communications; how rockets explore the upper atmosphere; the northern lights; the record of the glaciers; the cause of airglow; the earth's interior; deep ocean currents; the man-made moons (artificial satellites); and methods of geophysical prospecting.

Scene of the meetings will be the University of Toronto, with headquarters at Hart House. In charge of arrangements is PROF. J. T. WILSON, head of the Geophysics Laboratory of the University, who is also vice-president of the IUGG.

CODE OF ETHICS FOR COLLEGE RECRUITING

Concerned that the great demand for engineering graduates will lead to excesses in college recruiting, the American Society for Engineering Education and the Midwest College Placement Association have joined to prepare a new "code of ethics" entitled *Recruiting Practices and Procedures*.

The code says in effect that industry, colleges, and students must seek especially to be prompt, businesslike, and honest in their placement activities because of the temptations of today's keen demands for graduates.

Employers should avoid "elaborate entertainment and overselling." There should be no "special payments, gifts, bonuses, or other inducements," nor should there be reward for a third party who may prevail upon a student to accept an employment offer.

On their side, students "should not hoard or collect job offers." When a student accepts an offer he should let other prospective employers know his decision and he should not accept additional interviews. Students invited to visit plants or company headquarters should decline unless "sincerely interested" in working for the company, and their expense sheets for such trips should include only expenses directly concerned.

The colleges can help, says the new report, by encouraging both students and interviewers to be businesslike, by discouraging "indiscriminate shopping," by competently advising (but not "unduly influencing") students, and by giving interviewers complete information about graduating students.

The new "code of ethics" revises a March, 1949, publication of the American Society for Engineering Education. In a foreword to the new booklet, C. J. Freund, Dean of the College of Engineering at the University of Detroit and chairman of ASEE's committee on ethics, says, "Industrial employers are actively competing for the services of engineering graduates. In the stress of competition some employers have developed procedures which appear improper to others, particularly those with longer experience in visiting colleges to interview seniors.

"We hope that some of the present difficulties may be overcome by the new 'code of ethics,' adjusted to new conditions, in the same way that a previous publication was instrumental in solving similar problems of 1949," says Dean Freund.

Copies of the new "code of ethics," *Recruiting Policies and Procedures*, are available from the Secretary of the American Society for Engineering Education, University of Illinois, Urbana. Single copies are priced at 25 cents each, but substantial discounts are given for quantity purchases.

SOCIETY SCHOLARSHIP PROGRAM CONTINUES TO GROW

The Society of Exploration Geophysicists will administer undergraduate scholarships totalling at least $11,500 this year, it has been announced by Bart W. Sorge, chairman of the Public Relations Committee. The following contributions were received since publication of the contributors list in April, 1957 GEOPHYSICS: Southern Geophysical Co., Fort Worth, Texas, $500; The Superior Oil Co.,

Houston, Texas, $750; Texas Gulf Sulphur Co., Houston, Texas, $750; Schlumberger Foundation, Houston, Texas, $750; Well Instrument Developing Co., Houston, Texas, $100; and Exploration Sales Co., Houston, Texas, $25.00. Mr. Sorge also announced that the smaller contributions will be matched by SEG funds to provide an additional $500 scholarship, bringing the total to 13 awards sponsored this year by the geophysical industry.

SEG president Roy F. Bennett has appointed Mr. Sorge chairman of a committee to establish an "educational foundation" for the SEG with the primary function of administering the growing scholarship program. The committee will consider the broader purpose of encouraging expansion of geophysical education. The two other members of the committee are Richard Brewer, chairman of the Student Membership Committee which now administers the scholarships, and F. J. Agnich, who was chairman of that committee in 1956, the year the scholarship program was initiated.

SINCLAIR REFINING COMPANY FELLOWSHIP

The Sinclair Refining Company has established a graduate fellowship in geophysics at the New Mexico Institute of Mining and Technology, Socorro. Announcement of the fellowship was made recently by Dr. E. J. Workman, Institute president.

The fellowship, established initially for one year, will have an annual value of $2,500. The recipient is to be chosen by the chairman of the graduate faculty of the Institute. Under the terms of the grant, no services will be required of the holder of the fellowship.

The grant evidences the interest of the donor company in the geophysical exploration program conducted at NMIMT by Mr. Victor Vacquier and his associates.

PAN AMERICAN ANNOUNCES FELLOWSHIPS

Details of its fellowship program for the 1957–58 academic year have been announced by Pan American Petroleum Foundation, Inc., formerly Stanolind Foundation, Inc. The foundation was created and is supported by Pan American Petroleum Corporation.

Eleven of the foundation's 16 fellowships will be administered by officers at Fort Worth, Houston, Oklahoma City and Casper. The remaining five will be administered from the foundation's Tulsa office. Formerly all fellowships were under Tulsa jurisdiction.

Pan American Petroleum Foundation fellowships carry a stipend of $1,500 and pay costs of tuition and fees for each fellow. In addition, geology fellows are eligible for a $500 grant to cover costs of summer field work.

In the 21st year of its fellowship program, Pan American Petroleum Foundation offers grants in six fields of graduate study at 15 universities and colleges across the nation. In every case, graduate students are selected by the school.

Colleges and universities where the program is offered include the following:

University of Arkansas, chemical engineering; Kansas State College, chemistry; University of Oklahoma, petroleum engineering; Oklahoma A&M College, mechanical engineering; University of Tulsa, petroleum engineering.

University of Colorado, geology; University of Utah, geophysics; University of Texas, geology and petroleum engineering; Louisiana State University, geology; Texas A&M College, petroleum engineering.

California Institute of Technology, geophysics; University of California, geophysics; Columbia University, geophysics; Pennsylvania State University, petroleum engineering; and Yale University, geology.

SHELL COMPANIES FOUNDATION CONTRIBUTIONS

Shell Companies Foundation, Inc., has announced that its contributions to educational, charitable, religious and public service organizations will top the million dollar mark for the third straight year.

The amount, one of the largest in industry, is allocated from gifts made to the Foundation by the several Shell companies.

M. E. Spaght, executive vice president of Shell Oil Company and president of the foundation, said more than $500,000 will go toward educational programs.

Shell will provide 52 graduate fellowships and 20 grants for fundamental research to 43 colleges and universities and 90 full summer-term fellowships for high school science and mathematics teachers.

The foundation's merit fellowship program was inaugurated last year with 60 high school teachers attending summer seminar programs at Cornell and Stanford Universities. It was expanded this year to include 90 teachers.

This program was formed to help overcome the country's critical shortage of engineers and scientists. Selected high school teachers go to summer sessions to receive advanced training in their field, instruction in educational methods, and opportunities to meet leading scientists and to visit industrial plants and research laboratories.

Tuition, an allowance for transportation costs, living expenses and $500 additional in cash to make up for loss of potential summer earnings will be supplied the teachers by the foundation.

Shell hopes through its merit fellowship program to provide inspiration to those teachers who are in turn best able to inspire students to make science their career, Mr. Spaght said.

The graduate fellowship grants total $132,000 to assist in the post-graduate training of the outstanding students. Each fellow will receive $1,500 for his personal maintenance. His tuition and fees are also paid and an additional fund is supplied the designated department as a cost of education supplement. Schools not supported by taxes will receive a further supplemental grant for general administrative use.

The research grants total $150,000. Each grant consists of a donation of $5,000 to assist in expanding fundamental research and a supplemental donation of $2,500 for use in any manner the school determines.

Schools are given full responsibility and latitude in selecting both the regular term and summer fellows and utilizing the funds provided for basic research. Fields designated by the Shell Companies Foundation for 1957–58 regular term fellowships include chemistry, chemical engineering, geology, geophysics, mathematics, mechanical engineering, metallurgy, petroleum engineering, physics, plant science, and business administration.

Other schools and education programs will receive support through Shell gifts to the National Fund for Medical Education, the National Science Teachers Association, the Council for Advancement of Secondary Education, the Institute of International Education, Inc., the Council for the Advancement of Small Colleges, and the United Negro College Fund, Inc.

SHELL GRANTS FOR FUNDAMENTAL RESEARCH

ACADEMIC YEAR 1957–1958

School	*Field*
California Institute of Technology	Chemical engineering
California Institute of Technology	Physics
Carnegie Institute of Technology	Chemical engineering
Chicago, University of	Chemistry
Cornell University	Chemistry
Harvard University	Chemistry
Harvard University	Physics
Massachusetts Inst. of Technology	Chemical engineering
Massachusetts Inst. of Technology	Mechanical engineering
Massachusetts Inst. of Technology	Metallurgy-corrosion
New York Univ.—Inst. of Math. Sci.	Mathematics
Northwestern University	Chemistry
Notre Dame, University of	Chemistry
Princeton University	Chemistry

School	*Field*
Rice Institute	Mechanical engineering
Rochester, University of	Chemistry
St. Louis University	Geophysical engineering
Stanford University	Engineering mechanics
Stanford University	Geology
Yale University	Geology

RECAPITULATION BY FIELD OF STUDY

Chemistry	7
Chemical engineering	3
Engineering mechanics	1
Geology	2
Geophysical engineering	1
Mathematics	1
Mechanical engineering	2
Metallurgy-corrosion	1
Physics	2
TOTAL RESEARCH GRANTS	20
Schools represented—1957–58 Program	15

Note: The summer seminars for high school teachers of science and mathematics at Cornell and Stanford will be repeated in 1957. These merit fellowships will be expanded from 30 at each location for 1956 to 45 at each school for 1957. Shell's aid-to-education budgets for 1957, including other special donations made by the foundation, will approximate $500,000.

SHELL FELLOWSHIP PROGRAM

ACADEMIC YEAR 1957–1958

School	*Field*
California Inst. of Technology	Chemistry
California Inst. of Technology	Mechanical engineering
California, Univ. of (Berkeley)	Chemistry
California, Univ. of (Berkeley)	Mechanical engineering
California, Univ. of (Los Angeles)	Geophysics
California, Univ. of (Los Angeles)	Geology
Carnegie Inst. of Technology	Chemical engineering
Chicago, University of	Chemistry
Chicago, University of	Physics (non-nuclear)
Colorado School of Mines (Golden)	Geology or Geophysics
Colorado, University of (Boulder)	Chemical engineering
Columbia University	Geophysics
Cornell University—New York State College of Agriculture	Plant Science
Delaware University	Chemical engineering
Duke University	Physics (non-nuclear)
Georgia Inst. of Technology	Chemical engineering
Georgia Inst. of Technology	Civil engineering
Harvard University	Physics (non-nuclear)
Harvard University	Chemistry

School	*Field*
Illinois Inst. of Technology	Chemical engineering
Illinois, University of	Chemical engineering
Illinois, University of	Geology
Indiana University	Geophysics
Iowa State College	Chemistry
Kansas, University of	Geology
Louisiana State University	Geological eng. *or* petroleum prod. eng.
Massachusetts Inst. of Technology	Mechanical engineering
Massachusetts Inst. of Technology	Physics (non-nuclear)
Michigan, University of	Chemical engineering
Michigan, University of	Mechanical engineering
Minnesota, University of	Chemistry
Minnesota, University of	Geology or Geophysics
Nebraska, University of	Geology
Northwestern University	Geology
Ohio State University	Chemical engineering
Oklahoma, University of	Petroleum production engineering
Oregon State College	Mechanical engineering
Pennsylvania State University	Chemical engineering
Pennsylvania State University	Chemistry
Pennsylvania, Univ. of—Wharton School	Business administration
Purdue University	Chemical engineering
Purdue University	Mechanical engineering
Rice Institute	Physics (non-nuclear)
Stanford University	Geology
Texas, A&M College of	Petroleum prod. eng. *or* mechanical eng.
Texas, University of	Petroleum production engineering
Texas, University of	Geology
Washington University (St. Louis)	Physics (non-nuclear)
Washington, Univ. of (Seattle)	Chemistry
Wisconsin, University of	Chemical engineering
Wisconsin, University of	Chemistry
Yale University	Geology

RECAPITULATION BY FIELD OF STUDY

Chemistry	9
Chemical engineering	11
Civil engineering	1
Geology	10
Geology *or* Geophysics	2
Geological eng. *or* petroleum prod. eng.	1
Geophysics	3
Mechanical engineering	6
Petroleum production engineering	2
Petroleum prod. eng. *or* mechanical eng.	1
Physics (non-nuclear)	6
Plant science	1
Business administration	1
TOTAL FELLOWSHIPS	52
Schools represented—1957–58 program	38

ATLANTIC REFINING COMPANY GRANTS

The Atlantic Refining Company has announced it will award $12,500 in educational grants and scholarships this year to 16 colleges and universities in the South, Southwest, and Midwest as part of its annual aid to education program.

Six of the schools will receive $1,000 educational grants, three will get $1,000 graduate scholarships, and seven will receive $500 undergraduate scholarships.

The company since 1953 has made annual scholarship grants to schools in this area. This year, for the first time, it is supplementing its program with the educational grants.

Atlantic has designated the grants for departments teaching petroleum industry sciences. They are to be used solely at the discretion of the department and university to defray operating expenses, purchase needed equipment or supplement faculty salaries.

The 10 scholarships will go to promising students in fields of study directly related with the petroleum industry. Each institution will be the sole administrator of its Atlantic award and each will recommend its scholarship recipient on the basis of scholastic accomplishment in the department designated by the company.

Receiving $1,000 educational grants are Washington University, Geology; Rice Institute, Chemical Engineering; St. Louis University, Geophysics; University of Houston, Petroleum Engineering; University of Tulsa, Petroleum Engineering; Southern Methodist University, Mechanical Engineering.

Graduate scholarships go to A. & M. College of Texas, Electrical Engineering; University of Texas, Geology; University of Oklahoma, Petroleum Engineering.

Undergraduate scholarships are for University of Wyoming, Geology; Alabama Polytechnic Institute, Chemical Engineering; Louisiana State University, Petroleum Engineering; Colorado School of Mines, Geophysics; University of Kansas, Petroleum Engineering; Oklahoma A. & M. College, Mechanical Engineering; and Texas Technological College, Mechanical Engineering.

CONTINENTAL OIL COMPANY SCHOLARSHIP

Marietta College's Edwy R. Brown Petroleum Department has announced approval of an annual scholarship program with the Continental Oil Co.

The college will receive $1,000 annually, half of which is to be awarded to a senior candidate for a degree in petroleum engineering, and half to the college's petroleum department.

The $500 scholarship award is to be presented to a qualified student selected by the petroleum department and is to be used for furthering the student's studies during his final academic year.

A supplementary $500 grant is to go directly to the college for use in the petroleum department.

NSF SUPPORTS STUDY OF ENGINEERING EDUCATION

A $10,000 grant of the National Science Foundation will support the first phase of a comprehensive study of how American engineering colleges may attract and keep top-flight engineering teachers for their growing numbers of students.

The American Society for Engineering Education, sponsor of the project, says the Science Foundation grant will be used for preliminary work on a study "to determine and describe in detail the character and magnitude of the manpower and related financial needs of engineering colleges" and for organizing a full-scale attack on the problem.

When these needs are better understood, the society's project will go on to identify and specify the problems to be solved in meeting these needs, to determine and describe the special opportunities, satisfactions, and problems of engineering teaching, and to formulate the conditions which engineering colleges must fulfill to attract and develop good teachers for their faculties.

Dr. W. L. Everitt, Dean of the College of Engineering at the University of Illinois and president of the American Society for Engineering Education, announced the grant of the National Science Foundation last April. "This study of recruiting, developing, and utilizing engineering faculties," he said, "comes at a time when the competition for men to serve in these faculties is becoming increas-

Receiving silver recognition certificates for 25 years of service and membership in the Society of Exploration Geophysicists are (left to right) C. C. Zimmerman, Keystone Exploration Co.; Dave P. Carlton, Consultant; Fabian M. Kannenstine, Kannenstine Laboratories; and Derry H. Gardner, Humble Oil and Refining Co. Presentation was made by J. E. "Sam" McGee (second from left), past president of the Houston Section. Out of the city but receiving awards were Hart Brown, Brown Geophysical Co.; John S. Ivy, Consultant; and Eugene Leonardon, Schlumberger Well Surveying Corp. Awards were made before a meeting of about 300 members of the Houston Section, Friday, March 8, 1957.

ingly acute and when greatly increased numbers of students requiring even larger faculties in our engineering schools are in immediate prospect."

The ASEE project, titled officially The Development of Engineering Faculties, is under the direction of an executive committee of which Dean Harold L. Hazen of the graduate school at the Massachusetts Institute of Technology is chairman. Dr. William H. Miernyk of Northeastern University is executive director. The facilities of Northeastern's Bureau of Business and Economic Research, of which Dr. Miernyk is director, will be used.

The American Society for Engineering Education has the support of the Engineers Council for Professional Development, Engineers Joint Council, and the National Committee for the Development of Scientists and Engineers in the project, and the committee will work in "closest cooperation" with all other agencies concerned with problems of engineering and scientific manpower.

"The first step in the project," said Dean Hazen, "is to find out in some detail what shortages now exist and how great are the faculty needs now anticipated by engineering colleges." It is to start this study and to make detailed plans for subsequent phases of the project that the National Science Foundation grant is to be used.

While the committee will study the results of all available recent surveys of engineering and scientific manpower, it is undertaking a special study of its own, covering all engineering colleges in the United States, to obtain statistics on the estimated needs for engineering teachers throughout the

coming decades, their areas of special interest and competence, the qualifications they must have, their salary requirements, and—most important—the cost of meeting these needs.

In addition, to learn the many subtle and intangible aspects of this complex problem, the committee will make personal visits to a small but representative number of institutions.

"Only as these questions of needs have been thoroughly explored," said Dean Hazen, "will we begin to see how these needs may best be satisfied and what are the specific problems which should be of greatest concern."

The committee expected to make a progress report of its work at the ASEE annual meeting at Cornell University in mid-June.

Other members of the project's executive committee are Dr. Joseph C. Boyce, vice president of Illinois Institute of Technology; Dean Gordon B. Carson of the college of engineering, Ohio State University; Morris D. Hooven of the Public Service Gas and Electric Company, Newark, New Jersey, president of ECPD; and Dr. William C. White, vice president of Northeastern University.

SOUTHERN GIVES FILM TO HOUSTON STUDENT SEG

"Operation Swamp," a sound and color motion picture, has been added to the film library of the Rice Institute and University of Houston student section of the Society of Exploration Geophysicists, as a gift of Southern Geophysical Company.

Calling the movie "a field trip on film," John L. Bible, Southern vice president, said it was made a permanent library gift to enable a greater number of students to observe actual geophysical operations in the field.

The 15-minute documentary was filmed in the fall of 1956 on location in South Louisiana as Southern Geophysical seismic and gravity meter crews surveyed the marshes and swamps seeking possible oil bearing underground structures.

Bible and G. J. Long, Southern executive vice president, made the presentation at a meeting of the student SEG on the University of Houston campus. Dr. T. N. Hatfield of the U. of H. Physics Department, and Dale Miller of Rice, president of the student section, accepted the film for the SEG.

1957 DATA HANDLING WORKSHOP
GEOPHYSICAL EXPLORATION ROUND TABLE
INSTRUMENT AND AUTOMATION CONFERENCE

Cleveland, Ohio, September 9, 10, 1957

Dr. Simon Ramo's keynote speech will open a program providing an unusually broad opportunity for inter-industry cross fertilization of data handling techniques. Organized in a series of small "vertical" and "horizontal" sessions, the workshop panel discussions will cover data handling technology of many fields.

The geophysical exploration panel includes:

1. J. D. Skelton, The Carter Oil Co., "Magnetic recording and seismogram cross sections."
2. R. A. Broding, Century Electronic and Instruments, Inc., "Non-photographic recording methods."
3. S. C. Mut, The Atlantic Refining Co., "Digital computation of synthetic seismograms from continuous velocity logs."
4. Dr. Martin Packard, Varian Associates, "The measurement of the earth's magnetic field at very high altitudes."
5. Don Prell, Benson-Lehner Corp., "High-speed seismograph section plotting, including migration."

Round-table discussions and audience participation are features of the conference. Geophysical industry members are urged to attend and discuss their data handling problems.

PERSONAL ITEMS

R. E. SHERIFF, formerly geophysicist for The California Co., New Orleans, has become senior geophysicist for the California Exploration Co., San Francisco, California. Mr. Sheriff resigned as vice president of the Southeastern Geophysical Society because of the move. He was "second in command" of the program committee for the 1956 annual SEG meeting.

WAYNE A. PHARES, exploration consultant, has moved from Paola, Kansas to Seabrook, Texas.

A NEW ORGANIZATION has been formed by three geophysical companies to provide world-wide geophysical exploration services. Known as NAMCO International, the new organization represents the combined facilities and services of National Geophysical Company, Inc., Dallas, Texas, E. V. McCollum & Co., Tulsa, Okla., and Continental Geophysical Company, Fort Worth, Texas.

According to John Gillin, president of National Geophysical, each of the concerns involved will continue to operate as an independent company in the handling of domestic and Canadian geophysical work but will pool resources for international activities.

The election of W. J. HARKEY and HARRY L. JOHNSON as vice presidents of National Geophysical Company, Inc., has been announced by W. R. MITCHELL, executive vice-president of this Dallas-based geophysical exploration company. Mr. Johnson, who is in charge of the National's Houston office, supervises the Texas, Louisiana and other Gulf Coast activities; Mr. Harkey is located in Dallas where National maintains its headquarters.

DOYLE D. MIZE, president of Electro-Technical Labs., division of Mandrel Industries, Inc., has announced that the company has moved to its new plant at 5134 Glenmont Drive, Post Office Box 13243, Houston, Texas.

P. H. GARRISON has been named geophysical supervisor in the Tulsa general office of Pan American Petroleum Corp. He comes to Tulsa from Calgary, Alberta, where he had been Canadian division geophysical supervisor. In his new assignment, Garrison will be responsible for over-all coordination of Pan American geophysical operations in the United States and Canada.

C. A. WILLNER has been named division geophysical supervisor and M. R. HEWITT has been appointed district geophysicist in the Pan American Petroleum Corp. North Canadian district. Willner was formerly district geophysicist at the North Canadian district, and Hewitt was formerly staff geophysicist at the same office. The North Canadian district office is in Calgary, Alberta.

TWELVE SEISMIC AND GRAVITY SPECIALISTS have been transferred to Bolivian and Brazilian crews of Seismograph Service Corp. MICHAEL W. TYRRELL will lead a gravity party of seven men to Bolivia. The six others include JOHN W. CHOVIN, gravity computer, FREDERICK W. DOLL, ROBERT S. PLUMB, and ROBERT C. OBERG, gravity surveyors, CLINTON W. BROWNELL, gravity meter operator and HERBERT E. SMITH, gravity mechanic.

The five men transferred to the Brazilian crews include party chief ANTHONY J. KOCHENDORFER, RICHARD W. DUNBAR, observing supervisor, CHARLES G. LAIRD and PHILIP A. REHIL, observers and R. W. IVEY, driller.

KENNETH W. PAUL, formerly geologist with Shell Oil Company, has joined the Houston office of H. Zinder & Associates, Inc. as geological engineer.

KARL DYK, former vice president of SEG, is listed as an important contributor to the work of the U. S. Coast and Geodetic Survey in an article in the February issue of the "United States Naval Institute Proceedings."

The article, "Coast and Geodetic Survey," was written by Captain Elliott B. Roberts, USCGS chief of geophysics, in honor of the 150th anniversary of the U. S. agency.

Dr. Dyk, chief geophysicist for Pan American Petroleum Corp., Tulsa, is listed with other outstanding men who contributed to the work of the Survey. Dyk is cited in the article as the co-discoverer with Commander O. W. Swainson of the sound-propagation properties of water, the "wave-guide" phenomenon, in connection with research he and Swainson were conducting in radio-acoustic ranging.

Radio-acoustic ranging is a system used by the Survey during the '30's for locating vessels conducting charting operations out of sight of land. During World War II, it had limited use as an aid to locating fliers downed in the sea. Radio-acoustic ranging has since been replaced by a variety of electronics systems.

Dyk was employed by the Survey from 1933 to 1935, and he and Swainson discovered the "wave guide" phenomenon while experimenting in 1933. Since 1935, Dyk has been employed by Pan American Petroleum Corp.

HEADQUARTERS FOR THE PRODUCTION AND EXPLORATION DEPARTMENT of the Lion Oil Division of Monsanto Chemical Company have been moved from El Dorado, Arkansas, to Houston, Texas.

President T. M. Martin announced that Lion's production and exploration department needs the advantage of being in an active oil locality where the opportunities of growth in both domestic and foreign operations are greater. Now that Lion has joined with several other companies in oil and gas venture in Venezuela and will probably enter into other foreign exploration in the Western Hemisphere, the importance of such a move has become more evident.

E. D. KLINGER, chief geologist, will be headquartered in Houston. The geophysical department will be separated from the department offices, and Herbert Schlundt will assume the supervision of the geophysical operations in the southern and central regions and be headquartered in Shreveport, Louisiana. Rollin E. Phipps will supervise the geophysical operations in the southwestern and Rocky Mountain regions and be headquartered in Denver, Colorado.

E. I. GRIZZELL of Corpus Christi has been promoted to the job of supervisor of the Independent Exploration Company. The announcement of Mr. Grizzell's advancement was made by T. I. (Pop) Harkins, president of Independent Exploration Company.

K. C. THOMPSON has been named geophysical supervisor for foreign operations by Pan American Petroleum Corp. He will be responsible for over-all coordination of the geophysical programs of Pan American subsidiaries operating in the Caribbean area.

Prior to his new assignment, Thompson had been in charge of geophysical operations in the company's Central division, headquartered in Oklahoma City.

J. N. WALSTRUM, formerly geophysical supervisor on the general office staff, succeeds Thompson in Oklahoma City. As division geophysical supervisor, Walstrum will direct geophysical operations in Oklahoma, Kansas, western Nebraska, Arkansas, northern Louisiana, Mississippi and Alabama.

WILLIAM H. COURTIER, chief geophysicist for Phillips Petroleum Co., Bartlesville, Oklahoma, has been chosen as one of the Erasmus Haworth Distinguished Alumni by unanimous vote of the Department of Geology staff at The University of Kansas. Announcement of the award was made by M. L. Thompson, chairman of the department, at the Kansas alumni luncheon held during the AAPG annual meeting last April. In presenting the certificate to Dr. Courtier, Dr. Thompson said "This is the highest recognition in our power to give, and we are pleased to designate you as one of this group." The certificate is inscribed " . . . in recognition of outstanding achievement in which application of geological training has had an important part."

M. LAWRENCE FULLER, a junior in the geophysics option in the School of Ceramic Engineering of the Georgia Institute of Technology, has been chosen to receive the first Jackson Geophysical Society Scholarship. Announcement of the award was made last May by Mark D. Butler, chairman of the scholarship committee of the Jackson Geophysical Society, Jackson, Mississippi.

Professor H. W. Straley, III, notified Mr. F. W. Forward, president of the Jackson Section, that Mr. Fuller was the unanimous choice of the faculty. He said "Mr. Fuller is vice-president of the Student Section, a member of Tau Beta Pi, and on the dean's list for the first term. He has worked in the field under the leadership of two of our staff, who consider him a most promising young man and the outstanding member of our class of 1958."

The award, $250 in cash, was provided from a fund established by members of the Jackson Section and their companies. Mr. Butler advises that sufficient funds are on hand to provide a similar award next year.

ROBERT L. SUGGS, was presented the William J. Kossler Award on May 9, 1957 at the annual meeting of The American Helicopter Society in Washington, D. C.

The award is given for the greatest achievement in practical application or operation of rotary-wing aircraft, the value of which has been demonstrated in actual service during the previous year.

Mr. Suggs is a pioneer in the use of helicopters for transporting men and equipment to offshore oil drilling sites since early 1954. Since 1949 he also has utilized helicopters in seismograph and gravity meter oil surveys both in the United States, South America, Central America, and Canada. He is president of Petroleum Helicopters, Inc., New Orleans and Lafayette, Louisiana.

S. J. PIRSON, professor of petroleum engineering at The University of Texas has made a round of visits to various technical societies during the past academic year, presenting his talk on "Comprehensive Well Log Interpretation." He appeared on October 23, 1956 before the Fort Worth Section of the AIME in Fort Worth, Texas; on January 23, 1957 before the Beaumont Geological Society in Beaumont, Texas; on March 13, 1957 before the Evangeline Section of the AIME in Lafayette, Louisiana, and on May 1, 1957 before the AIME Southwest Texas Section, Austin-San Antonio Group in San Antonio, Texas.

The subject matter of this talk is currently appearing as a series of three articles in *World Oil*.

The firm of Rupnik and Ballou has announced the addition of R. C. TUTTLE to their organization to assist in the evaluation of the geologic aspects of their consulting operations.

Promotion of GEORGE H. CLARK to assistant to general manager of The Texas Company's Producing Department, effective May 1, was announced by J. N. Troxell, general manager of the department.

It also was announced that O. B. HOCKER will succeed Mr. Clark as assistant division manager, South Texas Division of the Producing Department on the same date. Both will be located at Houston.

T. L. KUNKEL has been promoted to chief geophysicist of The Texas Company's Producing Department, effective May 1, it was announced by J. N. Troxell, general manager of the department.

THE APPOINTMENT OF RONALD L. FOULK of Toledo, Ohio, as sales engineer in the eastern United States for Koenig Iron Works, Inc., has been announced by William S. Howe, sales manager for Koenig's domestic and foreign operations.

V. L. "VIC" JONES presented two papers before the seminar group at St. Louis University on April 30th. The titles of Vic's papers were "Correlation of Adjacent Gravimeter Surveys," and "Geophysical Prospecting in Northeastern Oklahoma." Vic also presented a paper before the Okmulgee Geological and Engineering Society on March 20th. The title was "Gravity and Magnetic Prospecting in Northeastern and Central Oklahoma."

CALENDAR OF MEETINGS

1957

September

3–14 International Union of Geodesy and Geophysics, Eleventh General Assembly, Toronto, Ontario, Canada (Dr. J. A. Jacobs, 49 St. George St., Toronto, Ontario, Canada)

5– 7 American Physical Society, Boulder, Colorado (W. A. Nierenberg, University of California, Berkeley 4, California)

October

6– 9 Society of Petroleum Engineers of AIME, Fall Meeting, Adolphus, Baker, and Statler Hilton Hotels, Dallas, Texas.

17–18 Southern California Petroleum Section AIME, Fall Meeting, Biltmore Hotel, Los Angeles, California.

24–26 Acoustical Society of America, Ann Arbor, Michigan (Wallace Waterfall, 57 East 55th St., New York 22, N. Y.)

November

4– 6 Geological Society of America Annual Meeting, Atlantic City, New Jersey.

6– 8 Gulf Coast Association of Geological Societies, Seventh Annual Convention, Roosevelt Hotel, New Orleans, Louisiana.

7– 8 Pacific Coast Section SEG, Autumn Meeting, Ambassador Hotel, Los Angeles, California (J. A. Hugus, Western Gulf Oil Co., 900 Wilshire Blvd., Los Angeles, California)

11–14 Society of Exploration Geophysicists, 27th Annual Meeting, Statler-Hilton Hotel, Dallas, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

11–14 American Petroleum Institute, 37th Annual Meeting, Conrad Hilton Hotel and Palmer House, Chicago, Illinois.

December

26–31 American Association for the Advancement of Science (Raymond L. Taylor, AAAS, 1515 Massachusetts Ave., Washington 5, D. C.)

1958

March

10–13 American Association of Petroleum Geologists, 43rd Annual Meeting, Biltmore Hotel, Los Angeles, California (E. Harold Rader, Standard Oil Company of California, 605 W. Olympic Blvd., Los Angeles 15, California)

April

17–18 Society of Exploration Geophysicists, Eleventh Annual Midwestern Meeting, Tulsa, Oklahoma (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

October

13–16 Society of Exploration Geophysicists, 28th Annual Meeting, Hotel Gunter, San Antonio, Texas (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

1959

November

9–12 Society of Exploration Geophysicists, 29th Annual Meeting, Biltmore Hotel, Los Angeles, California (Colin C. Campbell, Box 1536, Tulsa, Oklahoma)

* * * * *

July 1, 1957 to December 31, 1958

International Geophysical Year (Worldwide) *vide* GEOPHYSICS, v. 21, p. 257–259, and v. 21, p. 681–690 (H. Odishaw, National Academy of Sciences, Washington 25, D. C.)

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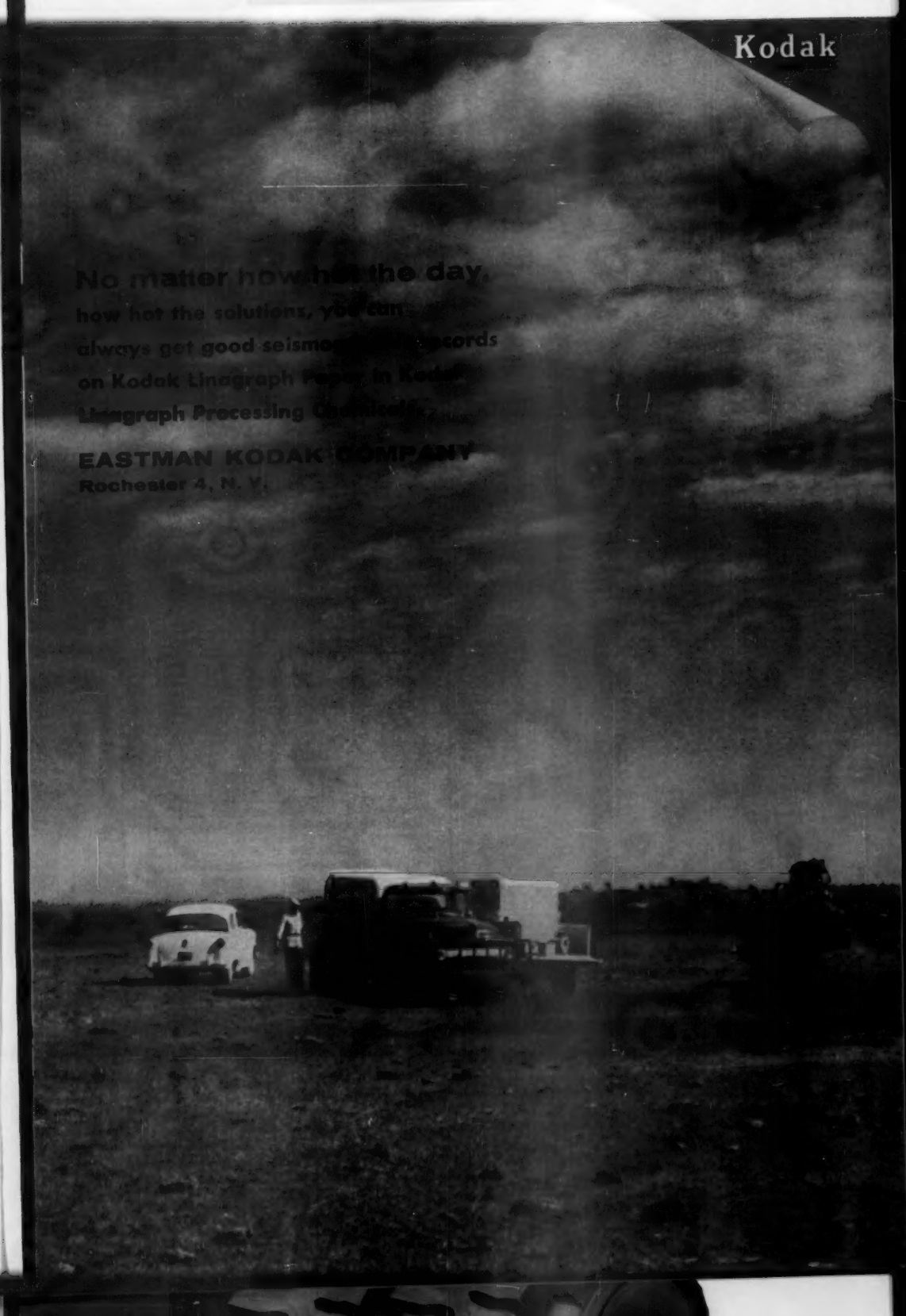

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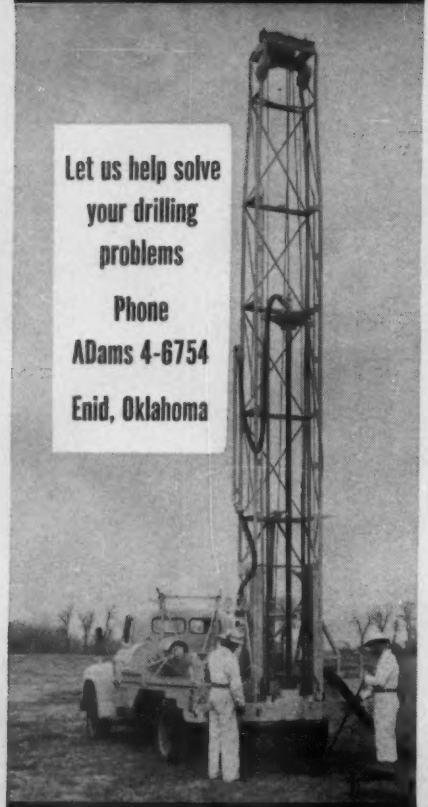

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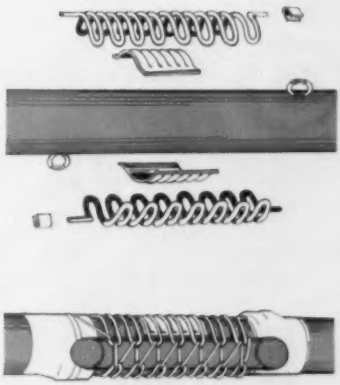

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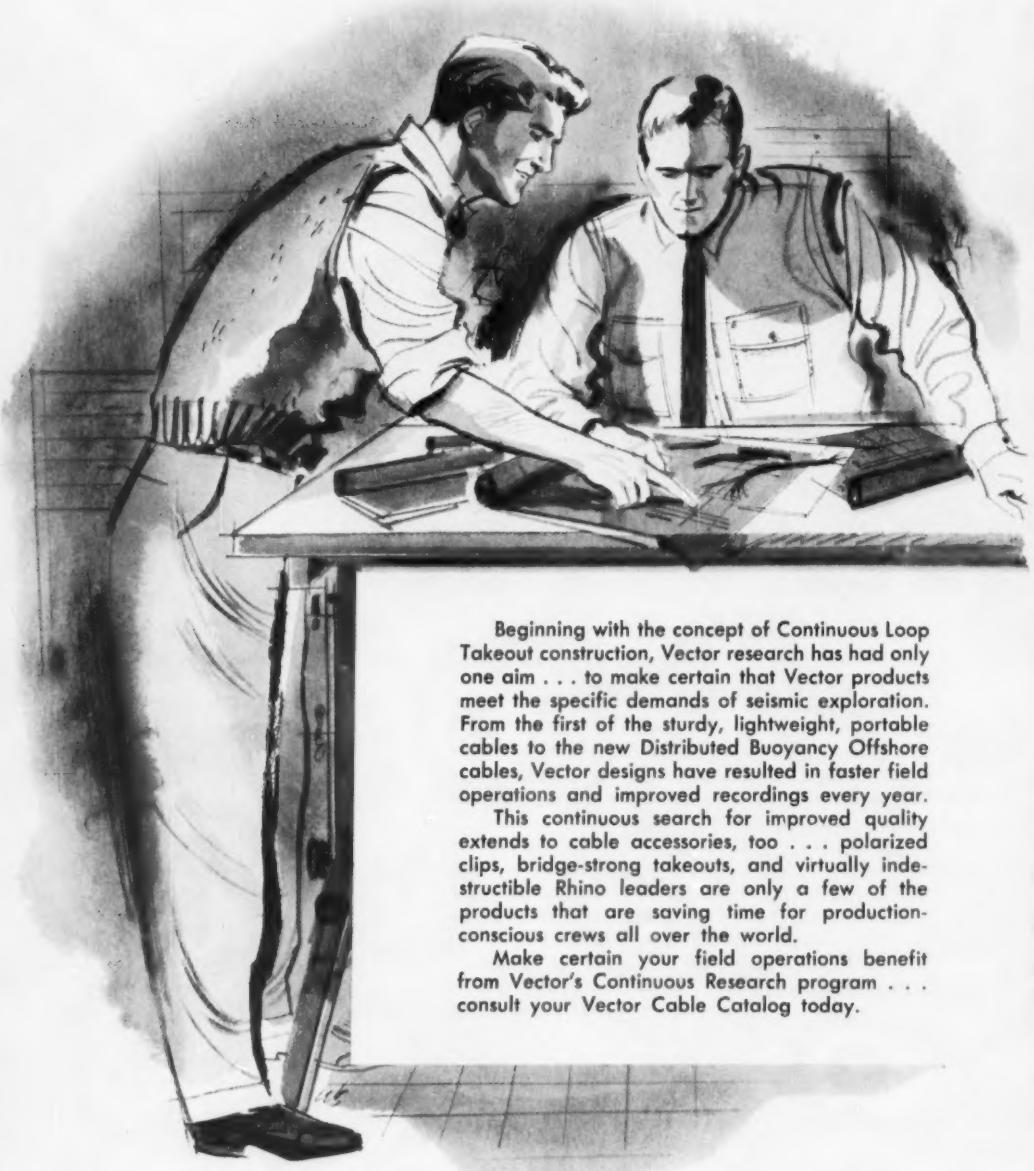

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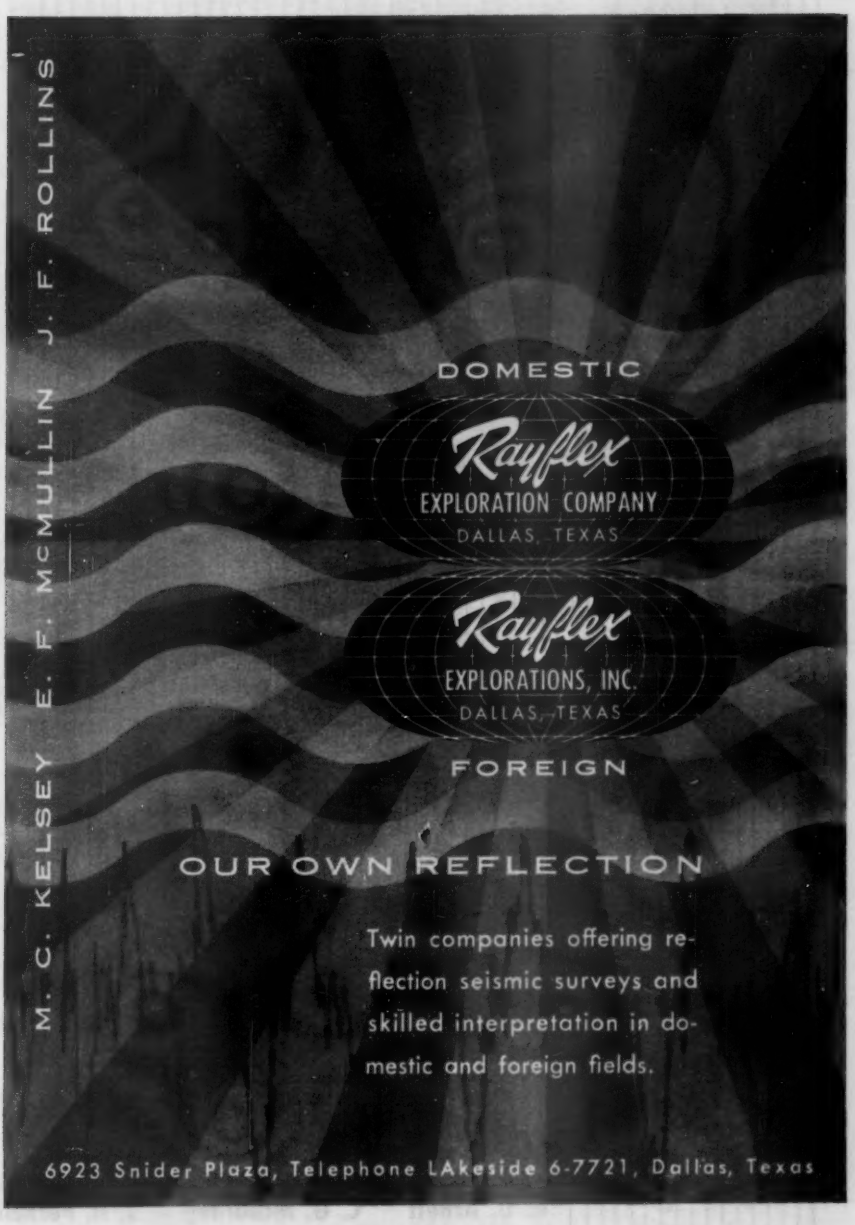
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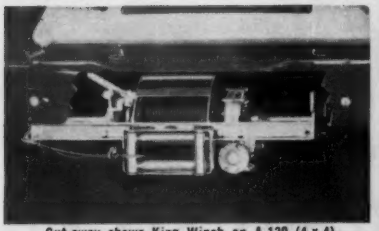

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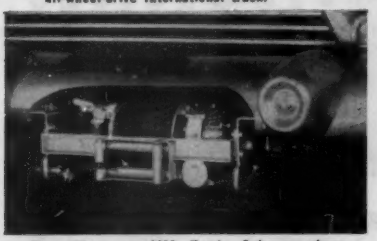

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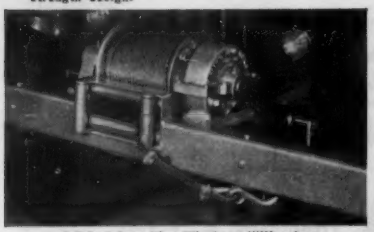

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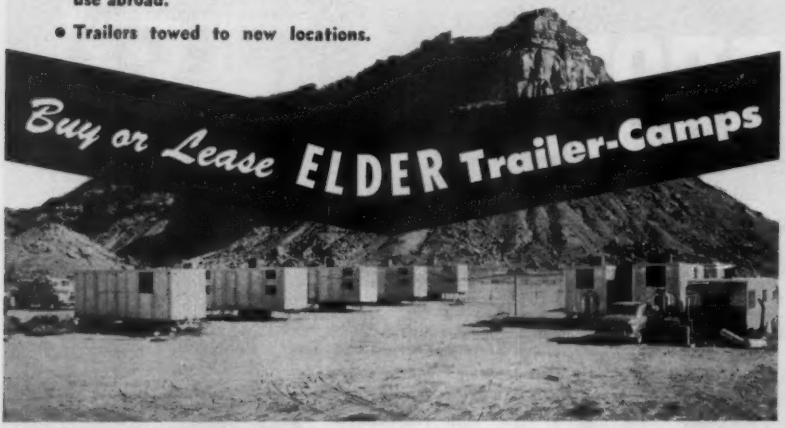

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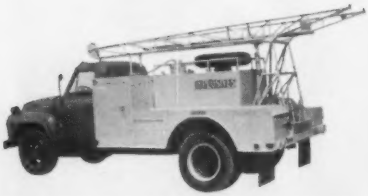

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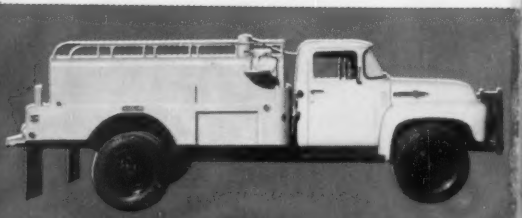

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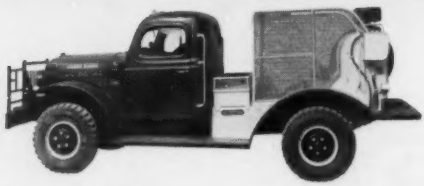

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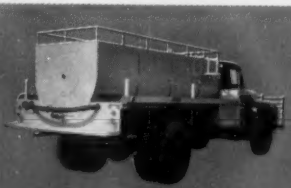

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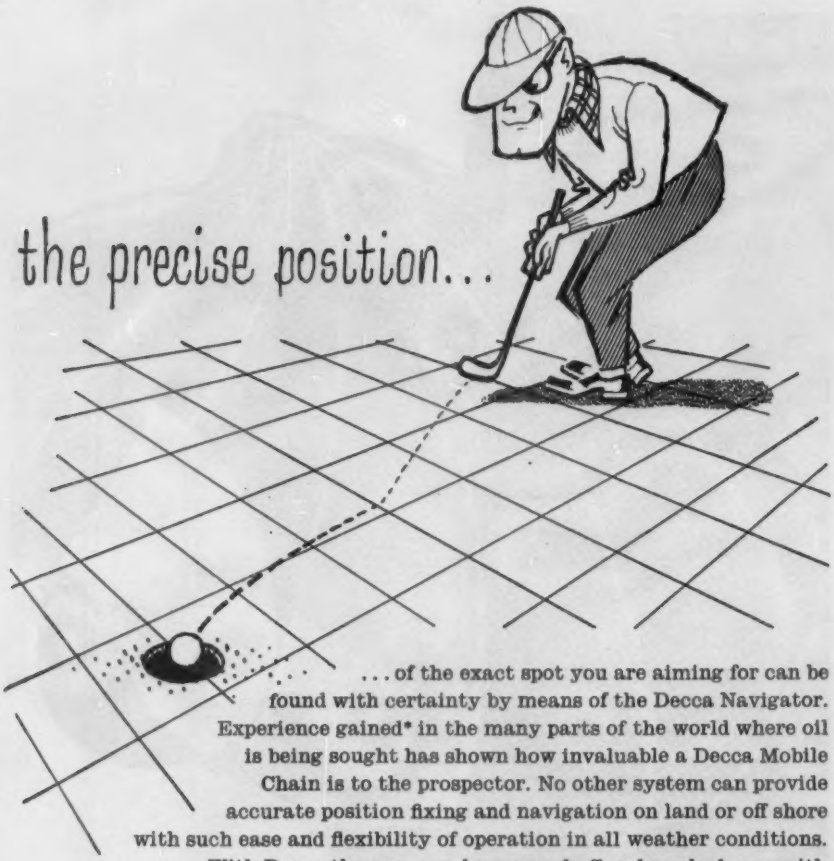

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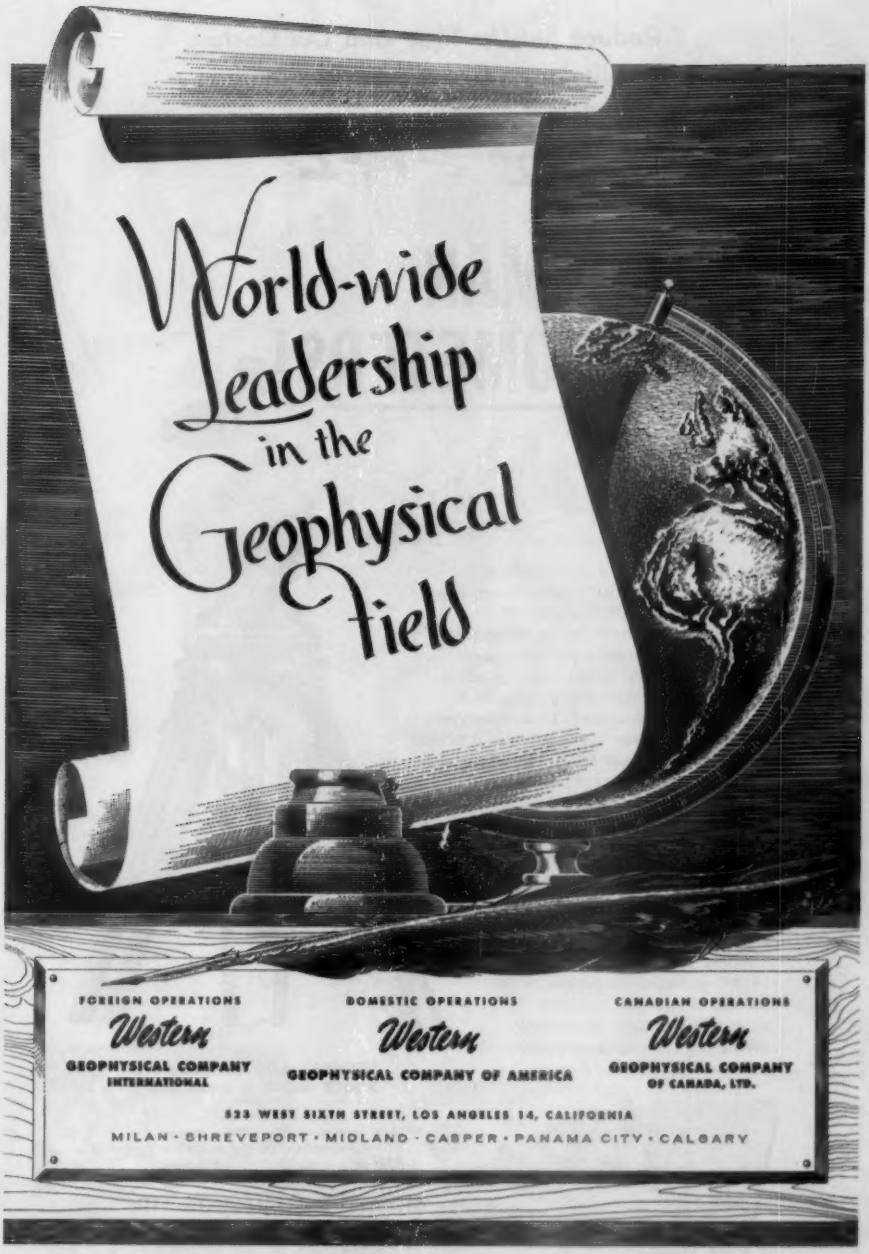
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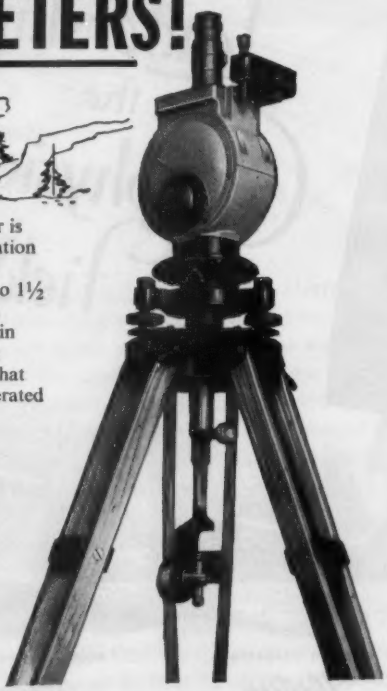

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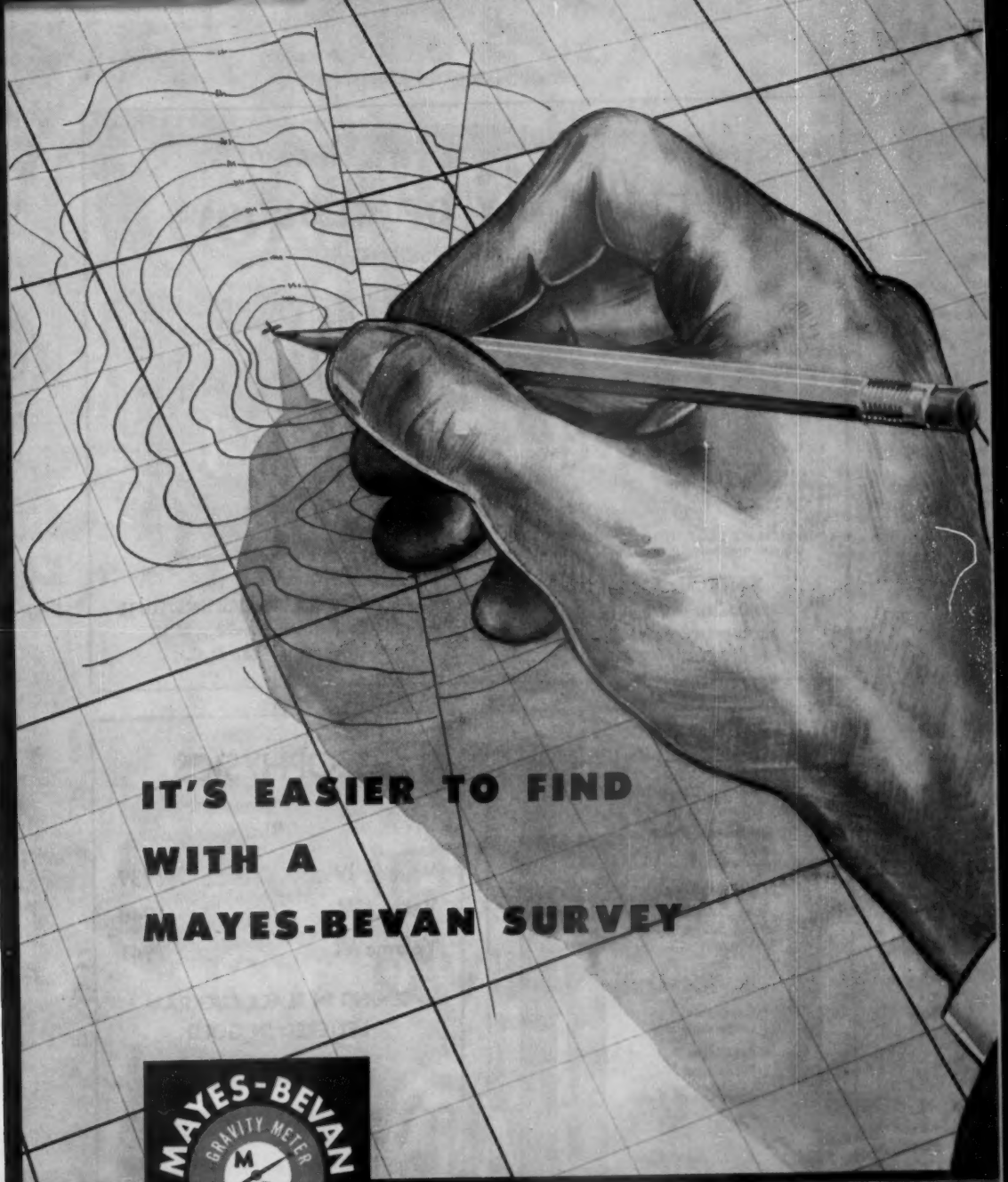

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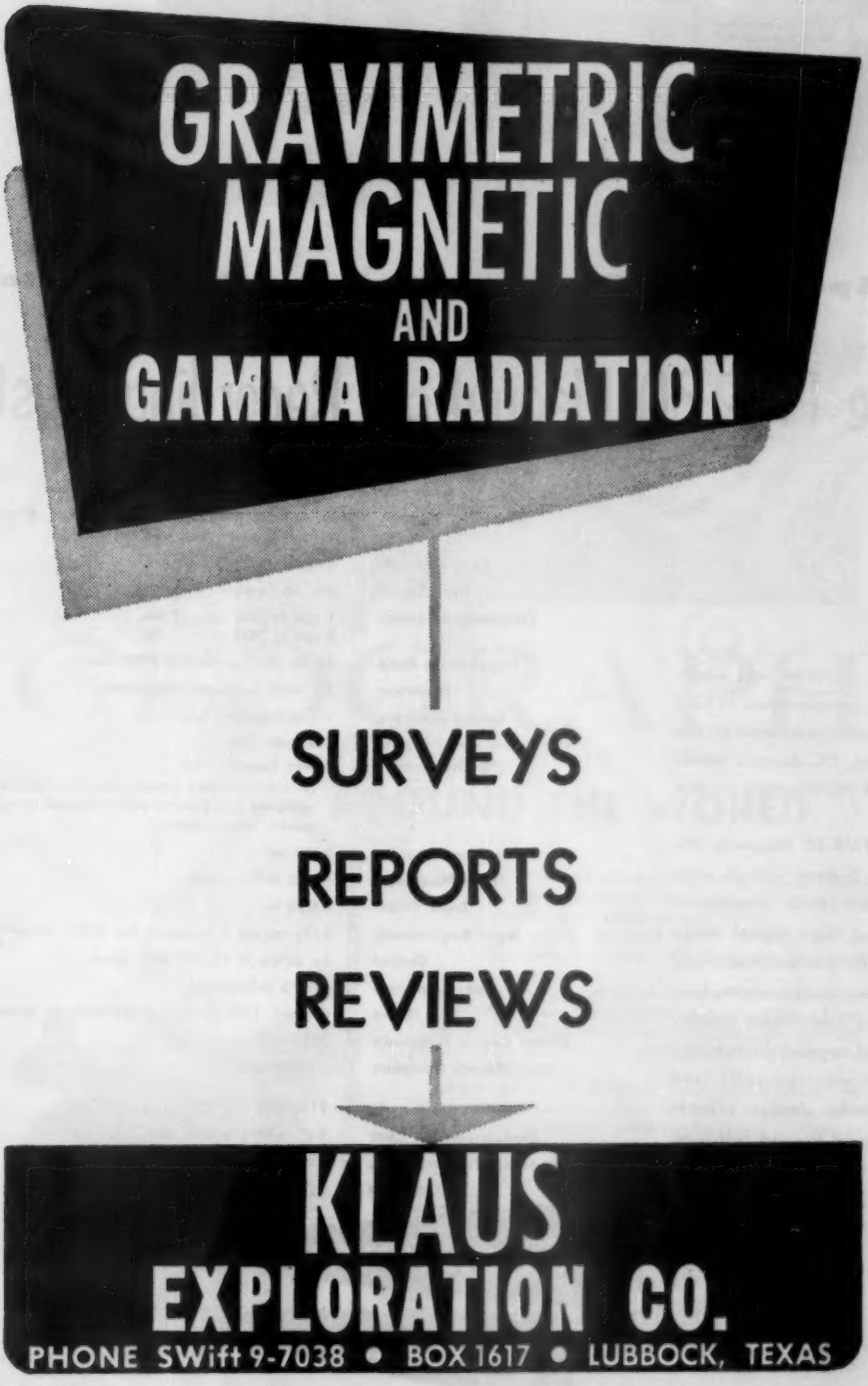

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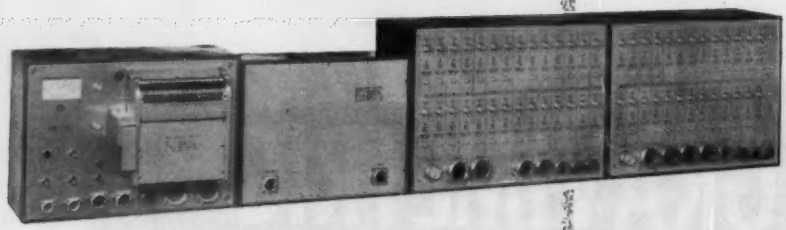

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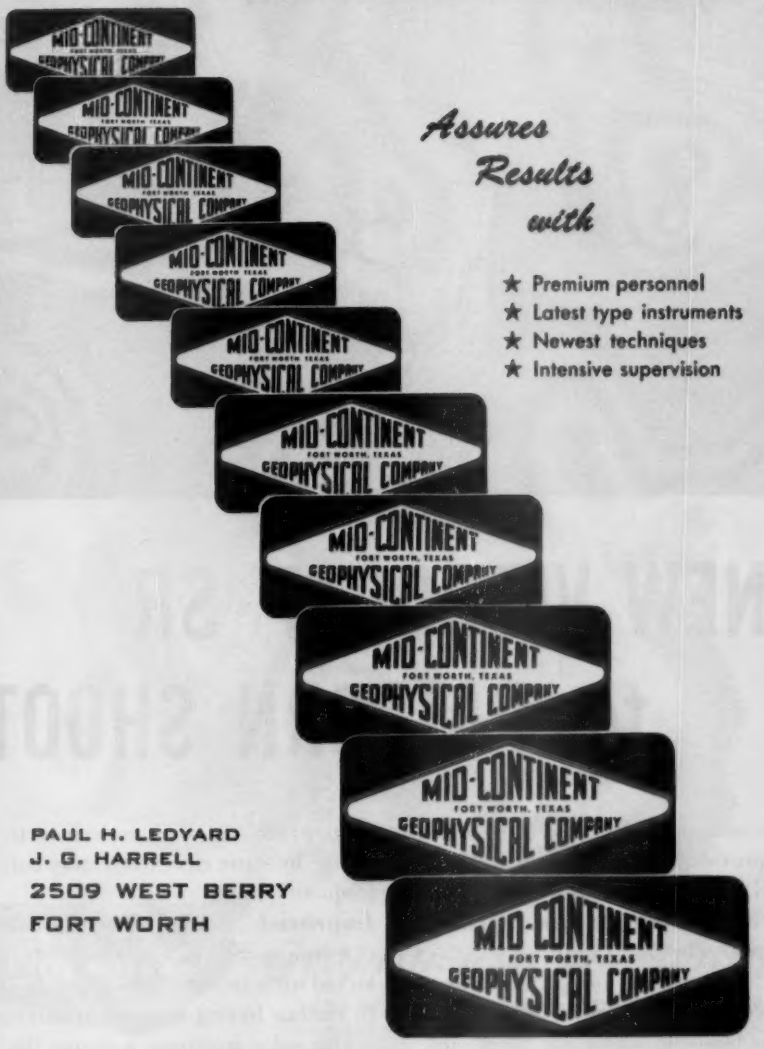

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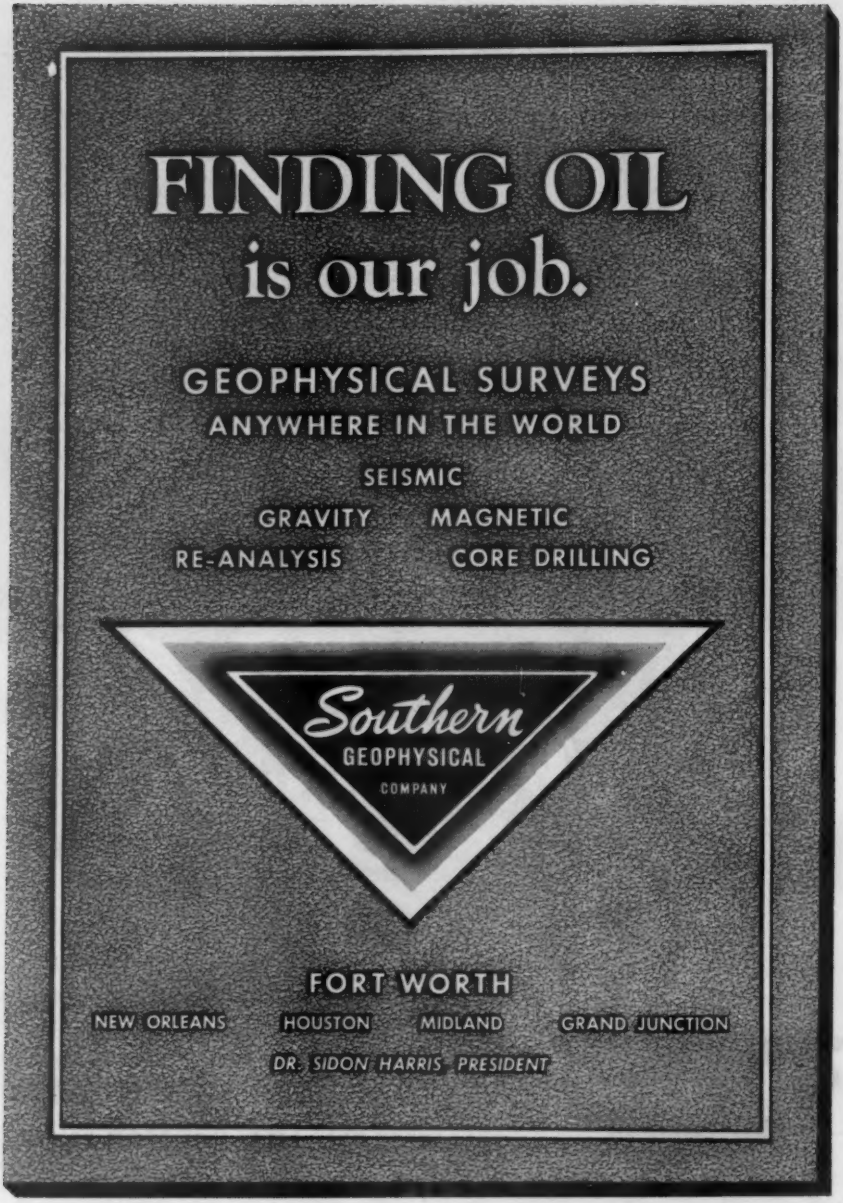
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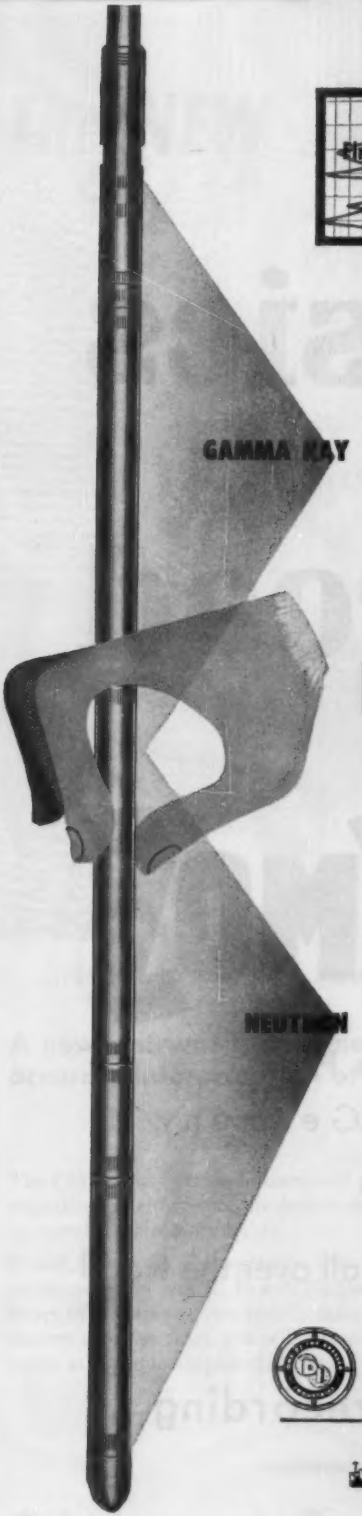

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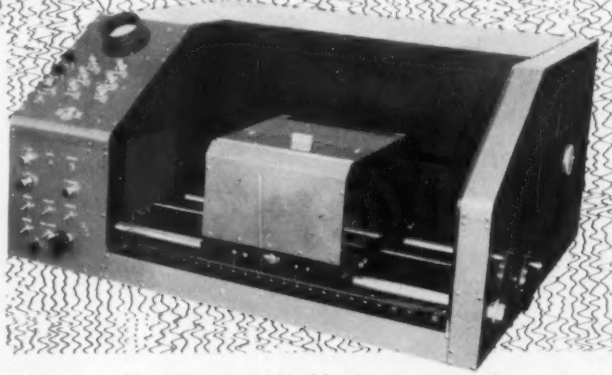

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The CMF Cross-Section Camera produces photographic records of seismic data as it is replayed from a group of magnetic tapes. When used with a tape reproducer which applies corrections for weathering, elevation and normal move out, the camera makes seismic cross sections which are very valuable for interpretational purposes.

Information from the magnetic tapes is displayed in the form of successive recordings, adjacent to each other on the same photographic sheet, using either conventional galvanometer (variable-amplitude) or variable-density traces. Optionally, through the use of a suitable optical system, variable-area traces may be made. The cross sections produced in this manner are 24 inches wide by 43 inches long, representing a recording time of 5.9 seconds.

More than 100 variable-amplitude traces may be recorded, using 1 to 24 galvanometers for each successive recording. Variable-density traces are recorded singly to a total of 400. When the camera is used for sequential trace recording, the static corrections (weathering, elevation, and move-out for any given time) may be included by appropriate setting of the recording drum position relative to the time break.

The recording paper is attached to a rotating drum, driven by a 110-volt synchronous motor. An aperture in the drum compartment allows the time lines and data traces to be recorded on the rotating paper. In front of the aperture is a unit which contains a variable-density glow tube, a timer glow tube, 24 galvanometers, and associated optical and electrical systems. This unit is mounted on horizontal bars and is positioned along the aperture by means of a lead screw. Accurate indexing shows the position of the data traces on the cross section.

Time lines are initiated by slots in a timing disc attached to the drum shaft, and are recorded on the cross section at 10-millisecond intervals with each 100-millisecond line accentuated.

A monitor-oscilloscope in the camera is used to align the time breaks on each successive recording, so that all portions of the cross section will have the same time reference. The drive motors of the camera and tape reproducer are synchronized by using a common power source, and gear ratios may be changed to maintain the required speed relationships.

The PAG Power Supply is a separate unit which provides the various voltages required to operate the camera.

SPECIFICATIONS

Variable-density Channels	400
Variable-amplitude Channels	128
Cross Section Width	24 inches
Cross Section Length	43 inches
Recording Time	5.9 seconds
Total Power	225 Watts
Dimensions... (inches)	18 x 33 x 38

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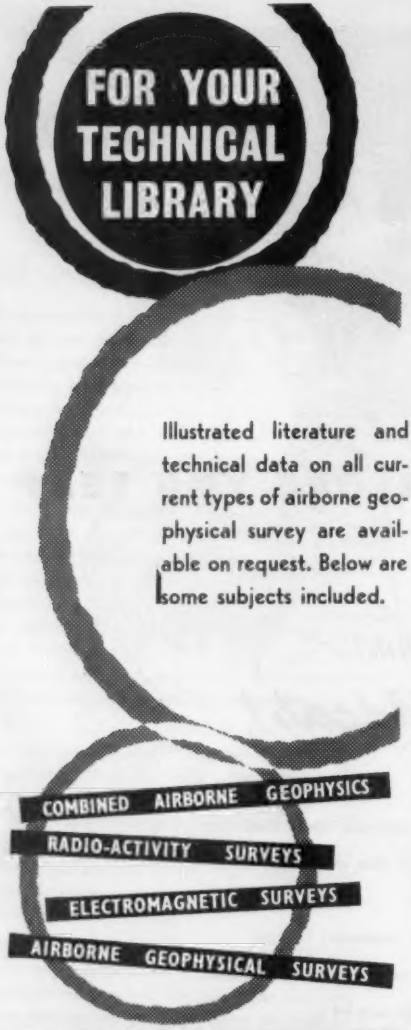
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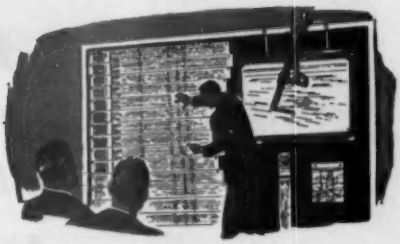

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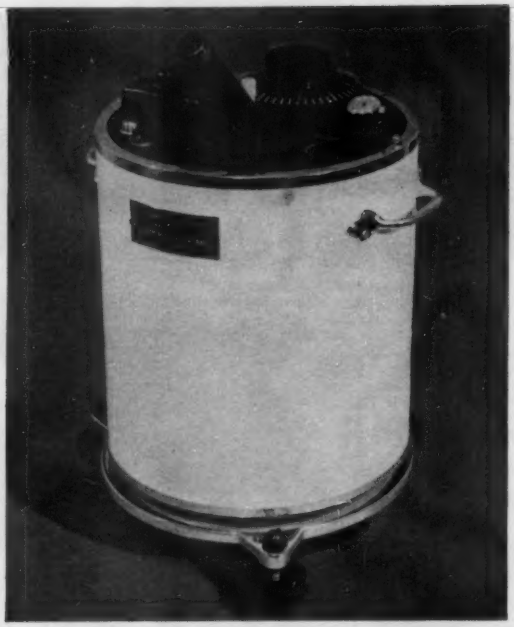

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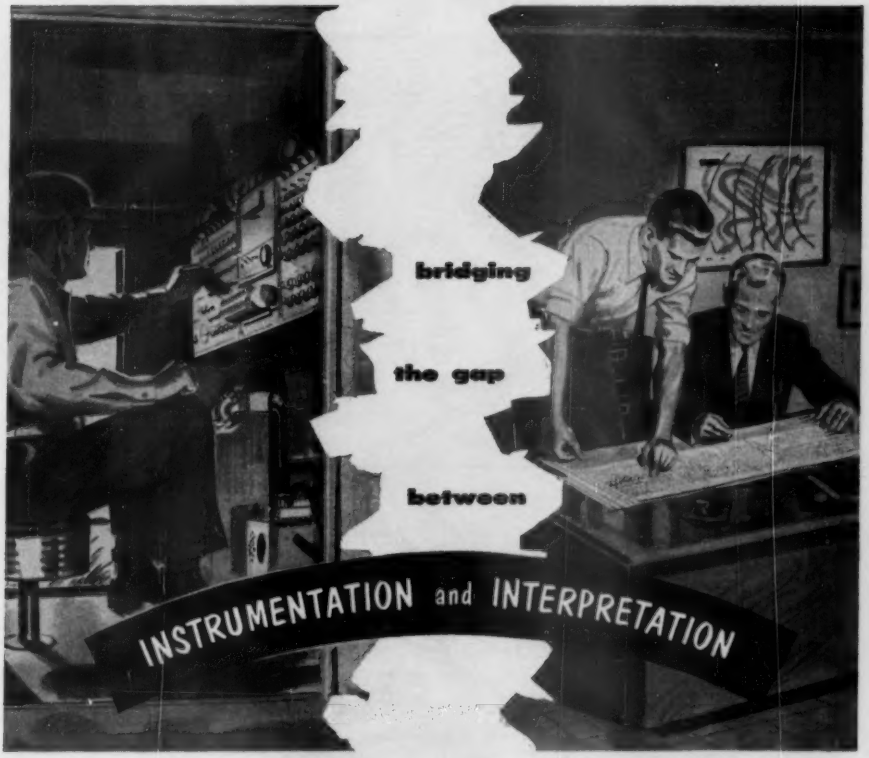

It is a known fact that geophysical instrumentation has advanced faster than geophysical interpretation. Due largely to the competitive efforts of specialized manufacturers, instrumentation has made significant strides in the past ten years. Whereas, interpretation has not kept pace.

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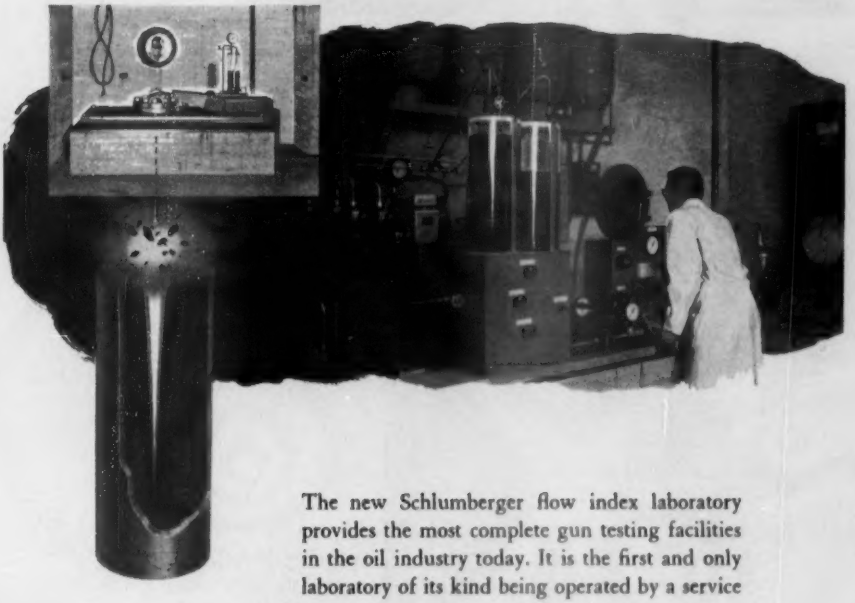

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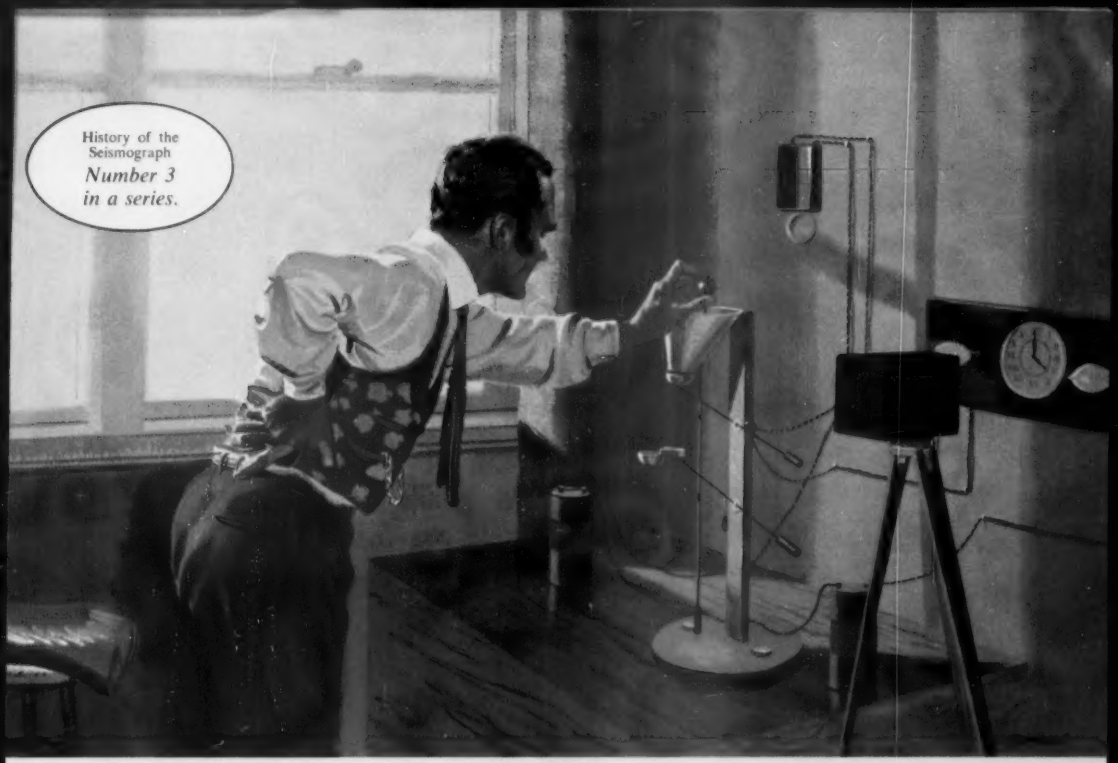

Pfaundler and the era of seismic clock stoppers!

In the late nineteenth century, several seismic devices were designed to record the exact time when seismic waves passed, rather than recording the intensity or direction of the waves. Von Lasaulx's instrument used a balanced egg-shaped mass which would fall from its resting place when seismic waves passed and trip a mechanism which stopped a pendulum type clock. Forster used an electromagnetic means for photographing the dial of a clock when the passage of seismic waves occurred. However, one of the most interesting is Pfaundler's "Goldberg-like" arrangement illustrated here.

Pfaundler used a vertical pendulum with a round mass balanced on the top. With the passage of seismic waves, the ball fell into the funnel and onto the cup-shaped end of a counter-balanced horizontal arm. As this arm tripped downward, switches were actuated which turned on the light bulbs at either side of the clock. Simultaneously, a camera focused on the face of the clock was snapped and recorded the time of the seismic waves. The ball continued on down to the second horizontal arm which in turn switched on an alarm bell.

In modern seismic explorations for oil, we are not only interested in recording the *exact times* of seismic waves, but also in converting these times to feet or depth. The T-Z (time-depth) Camera* developed by Texas Instruments converts seconds to feet by use of a controlled non-linear paper drive that is proportional to a selected velocity function. Thus the T-Z Camera used in conjunction with the seisMAC (seismic magnetic automatic computer) prepares *Depth* record sections in their most easily interpreted form.

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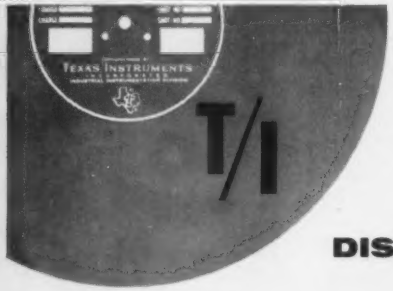

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Reliable and Rugged—No pampering required . . . no air-conditioned, dust-free, humidity-controlled environment is needed for accurate performance of the magneDISC.

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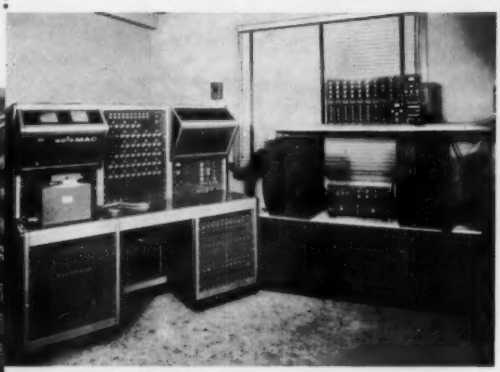
Recording Heads stay in precise alignment—discs can be played interchangeably on any magneDISC—tolerances are maintained to insure timing accuracy of ±½ millisecond trace to trace.



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The versatility of the magneDISC is unsurpassed in the CPO, used in conjunction with the seisMAC for automatic data reduction.

Speed of Processing—utilizing two 115 head magneDISC Transducer Units, data may be played from one through the seisMAC and re-recorded on the other in one continuous operation.

Greater Operational Latitude—two T/D Units provide 230 channels of information for mixing, compositing, or stacking as desired—no necessity for synchronization of several drums as with other systems.

Easier Handling and Storage—one movement of lever accurately positions disc in the T/D Unit—eject button pushes disc out for easy removal. magneDISCS take up less storage space than any other type of magnetic recording medium.

For complete information and the many other advantages of the magneDISC, write for Bulletin DS-307; or request a visit from the TI representative!

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* a Seismic system

The chance discovery of the pendulum *as a gravity instrument!*

When Jean Richer set forth for Cayenne, French Guiana, South America, in 1671, the thought that he would make a significant discovery about the earth's gravity never occurred to him. He carried a pendulum clock designed by Huygens to be used in the astronomical observatory at Cayenne.

The purpose of the expedition was to learn more about the size of the solar system. Specifically, Richer in Cayenne and Cassini in Paris were to make simultaneous observations of Mars at a given time and later compute its exact distance from the earth by triangulation. Richer observed that his clock, which had been correct in Paris, was slow, and had to have its pendulum shortened about 1/12-inch in order to tell the right time. When it was found that the length of a pendulum with a given period varied directly with gravity, it was realized that gravity must be less at the equator than in Paris. Newton and Huygens independently deduced that gravity variation is due in part to the departure of the earth from a spherical form.

Bouguer, some time later, learned of this clock which lost 2.5 minutes a day in French Guiana, but kept perfect time when returned to Paris. He was preparing for an expedition to test Newton's theories by measuring latitudes in Peru. He is credited with being the first to make relative gravity measurements using the invariable pendulum idea.

Now, the most popular instrument for weighing the world from poles to equator is the Worden Gravity Meter. More of these highly accurate instruments are in use for geodetic and exploration work than all other makes of gravity meters combined.

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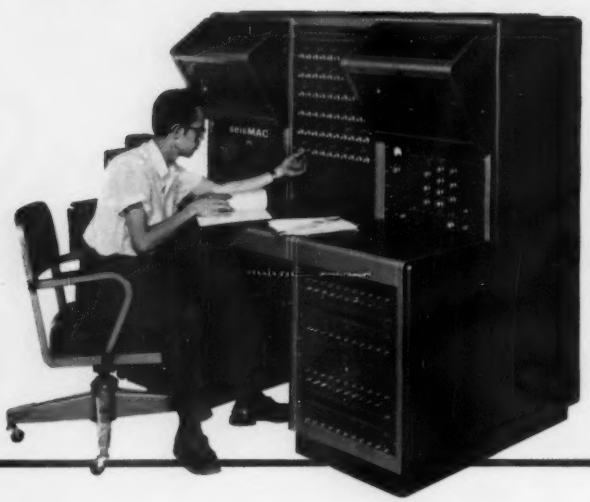
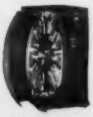


Other components in the TI-equipped Central Processing Office . . .



magneDISC . . . disc-type magnetic recorder

7000B "all purpose" seismograph system

T-Z (time-depth) Camera

The seisMAC, seismic magnetic automatic computer, developed by Texas Instruments Incorporated, is an analog data reduction machine controlled by a digital programmer. seisMAC provides for constant (weathering and elevation) and variable (normal moveout) corrections to be made to any number of seismic traces played back from the magneDISC or other magnetic recorder.

seisMAC, in conjunction with the other individual blocks used in the TI Central Processing Office (or a mixture of equipments, if desired), makes possible the preparation of either time or depth record sections with all the original character of seismic data preserved and the presentation enhanced. Some of the outstanding advantages of seisMAC which permit the presentation of data in its most comprehensible form for final interpretation by the geologist-geophysicist team are:

1. Constant and variable time corrections are made automatically.
2. Unlimited repeatability of data within one millisecond accuracy.
3. Provides 100 millisecond constant plus 100 millisecond variable corrections with no frequency, phase or amplitude distortion.
4. Adaptable with most magnetic transports.
5. Completely automatic during the processing — no adjustments need be made during the operation cycle.
6. No moving heads or cams to become misaligned — seisMAC is the first all-electronic system.
7. Immediate adaptability to any spread or velocity change.
8. Each trace is time-corrected sequentially and independently — no proportioning of a single NMO function for correcting inner traces.
9. Signal remains in analog form with digital programming — high speed processing, accuracy, and repeatability are inherent in the system.

For more complete information on the seisMAC and the TI-equipped Central Processing Office, write for Bulletin No. DS-318.

*TRADEMARK REGISTRATION APPLIED FOR

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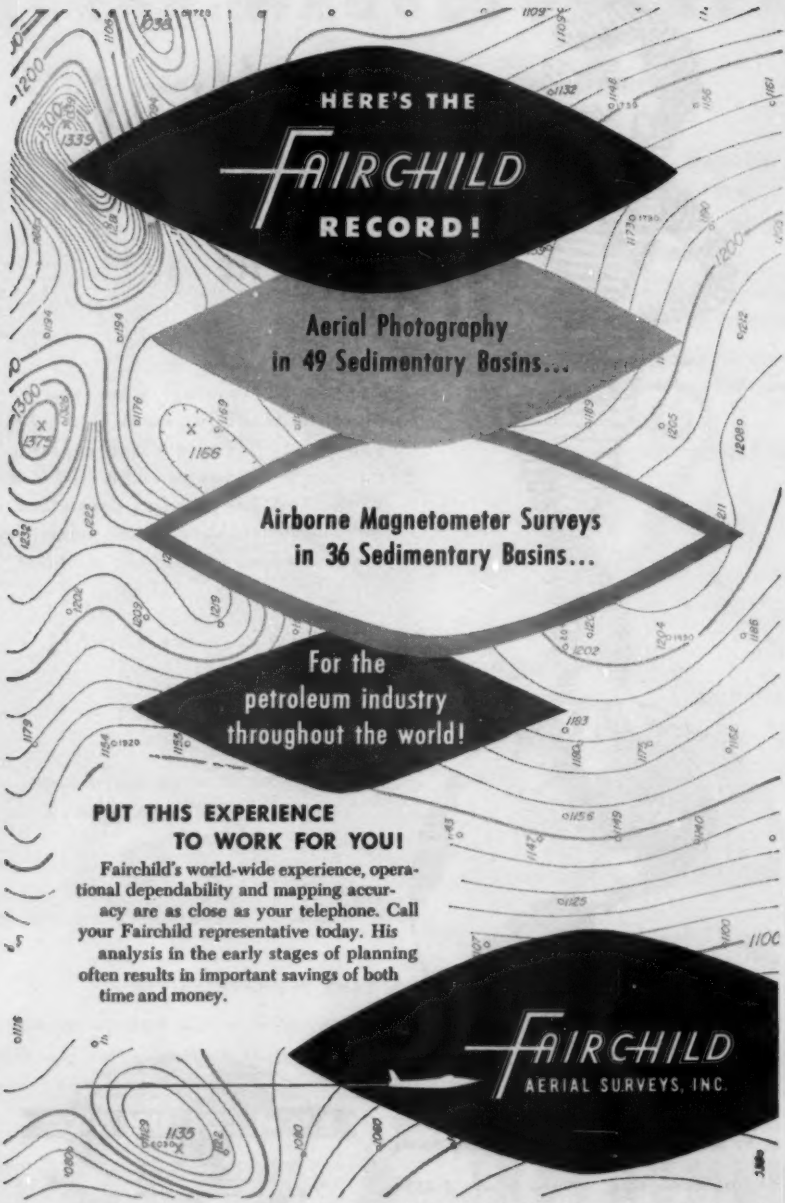
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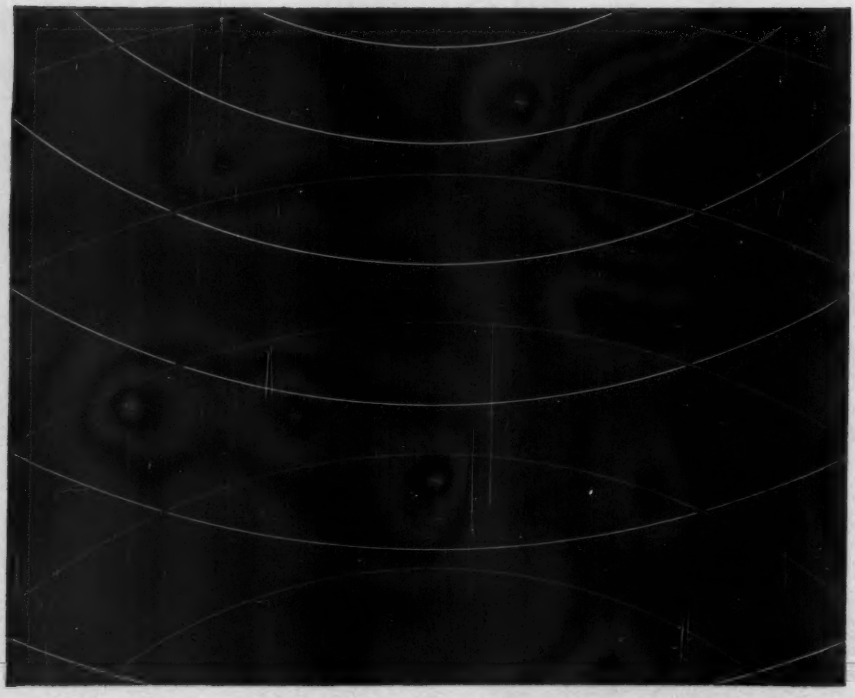

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Field party on survey for proposed Canyon Dam on Texas' Guadalupe River.

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W&T SURVEYING ALTIMETERS SPEED HYDROLOGIC STUDY OF RESERVOIR BASIN

A ground-water and geologic survey, involving water table isograms for 400 square miles adjoining the proposed Canyon Dam Reservoir on Texas' Guadalupe River, recently was completed in 35 days. Despite difficult terrain and maximum relief of 1000 feet, over three hundred spot elevations were taken during this period. The speed with which this work was done is attributed to the use of the two-base method of altimetry employing three Wallace & Tiernan Type FA-176 Surveying Altimeters.

Technical data on the FA-176 Altimeter include: **Range** — any interval of 2000' up to max. limit of 5000'; **Accuracy** — 2.0'; **Sensitivity** — 0.5'; **Scale Length** — 20"; **Dial Size** — 8½" dia.

For details on FA-176, send for Bulletin No. TP-7-A

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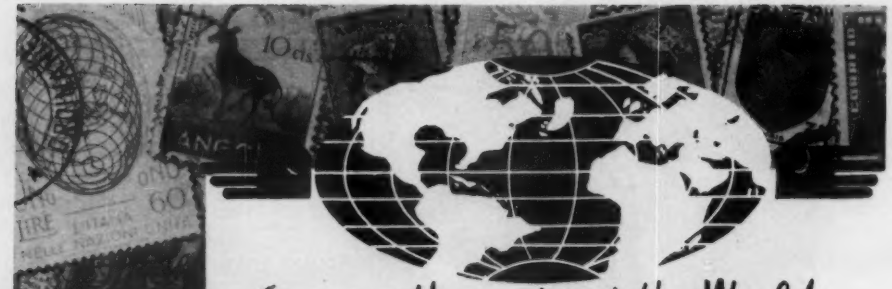

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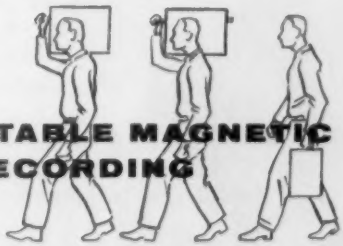
SIE

MAGNETIC RECORDING and ANALYSIS SYSTEMS

Here are some highlights from the SIE magnetic recording and analysis equipment program. To date, SIE has originated and is producing the most complete line of inter-related recording systems, tape transport devices, and data processing equipment available. Ranging from the compact PMR-7 Portable Magnetic Recorder for Direct Recording to the versatile MS-12 **GeoData** System, SIE magnetic instruments are designed to permit maximum flexibility in the choice of recording and analysis systems "tailor made" for the application. This program eliminates the purchase of equipment more elaborate than is necessary, and at the same time permits the addition of more complex recording and analysis instruments as required.

Whether your application requires a simple direct recorder or a complete office analysis system, be sure to contact SIE for full information when you plan your magnetic tape instrumentation program.



PMR-7 PORTABLE MAGNETIC DIRECT RECORDING SYSTEM

Three men can carry the complete PMR-7 Portable Direct Recording System including the 28 channel recorder, the PDA-2 Amplifier Unit, and the Power Supply. The recorder is available with fixed or movable head assemblies, and the records can be played back on an SIE Recorder or analysis system.

Designed for rough field duty, the PMR-7 utilizes magnesium and fibreglas construction for maximum strength in combination with light weight. Hermetic sealing of critical components, and water-tight case construction prevents moisture penetration even after submersion.

Judged by the toughest standards for field equipment: strength, durability and light weight; and meeting the famous SIE standards for recording accuracy and ease of operation, the PMR-7 meets every requirement of a modern seismic program.

SIE

MAGNETIC RECORD ANALYSIS SYSTEMS

SIE manufactures office playback and magnetic record analysis systems to cover a wide range of applications. Among the tape-transport systems used in these applications are the MR-5 twin-drum recorder and the MR-7 and MR-9 three-drum recorders. The design program behind these instruments has been planned to provide units which can be used separately or in groups depending on the application. This policy permits continuous development of new equipment which can be used with previous units, and enables users of SIE instruments to maintain greater flexibility in organizing their data processing equipment investment programs.

The MS-12 GeoData System, the most elaborate of these systems, provides time cross-sections, and normal moveout and weathering-elevation corrections, in addition to many other interpreting operations. Other Recorders and interpreting equipment are combined for office or field playback. Contact SIE for full information regarding these instruments and how they can be combined to provide a custom designed installation to meet all of your analysis equipment requirements.

SIE

GeoData

SYSTEM

MODEL MS-12

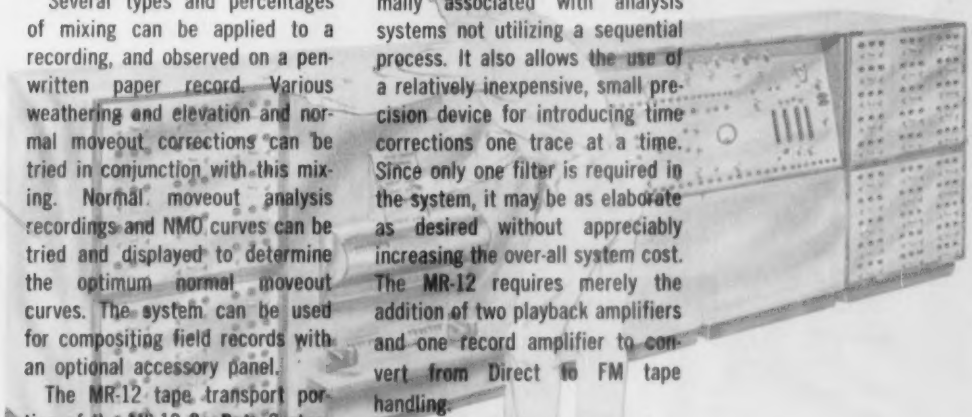
The MS-12 **GeoData** System processes FM and Direct recordings. It provides a record cross-section which is pen-recorded on paper and can be photographically reproduced. Cross-sections can be isopached or set to a desired reference plane. The graphically presented information is also permanently stored on magnetic records.

Magnetic or visual records which have been trace-mixed, filtered, corrected for weathering, elevation, and normal moveout can be made with **GeoData** equipment. Filter analysis may be made of field records by playing the same record back through several filters and displaying it as a pen-written paper recording.

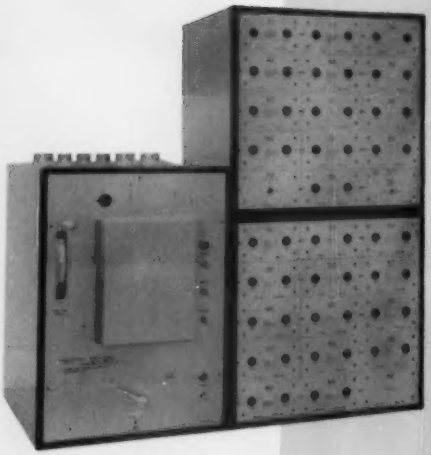
Several types and percentages of mixing can be applied to a recording, and observed on a pen-written paper record. Various weathering and elevation and normal moveout corrections can be tried in conjunction with this mixing. Normal moveout analysis recordings and NMO curves can be tried and displayed to determine the optimum normal moveout curves. The system can be used for compositing field records with an optional accessory panel.

The MR-12 tape transport portion of the MS-12 **GeoData** System consists of one field tape drum, one transfer tape drum and a wide cross-section plotter drum, all mounted on a common-driven shaft. The two standard SIE magnetic drums have adjustable combination FM and Direct recording head banks. The third drum is a 24-in. oscillographic drum for pen recording. Two galvanometer pen writers are provided for this visual display unit. One of these pens utilizes 2" of the oscillographic drum for monitoring purposes to observe time break, 100 cps reference signal and other information. The second galvanometer pen is used to display signal channels. The pen movement is adjustable to provide any desired horizontal scale for making cross sections.

The system is entirely sequential in operation in that it transcribes one trace at a time from the field tape, to either the transfer drum or the paper drum. This eliminates most of the many electronic amplifiers which are normally associated with analysis systems not utilizing a sequential process. It also allows the use of a relatively inexpensive, small precision device for introducing time corrections one trace at a time. Since only one filter is required in the system, it may be as elaborate as desired without appreciably increasing the over-all system cost. The MR-12 requires merely the addition of two playback amplifiers and one record amplifier to convert from Direct to FM tape handling.

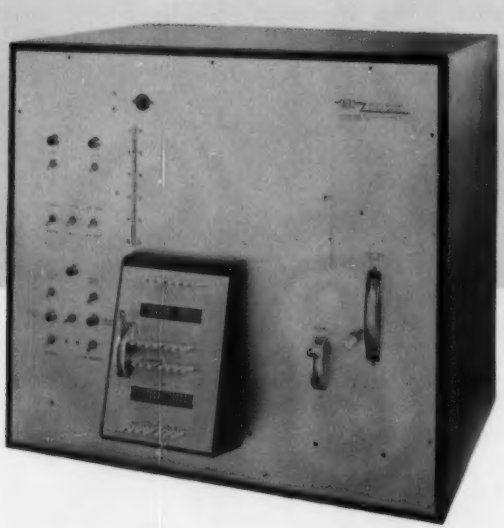


The MS-12 **GeoData** System provides an unchallenged achievement in providing application flexibility for every interpretation and analysis program. For full details, contact SIE or your nearest representative.



THE MOST VERSATILE FIELD RECORDERS AVAILABLE

MR-4 and MR-8D



The Famous MR-4 Recorder has been first choice with leading geophysical organizations for more than two years. Outstanding in terms of low noise level and distortion, its rugged construction and field dependability have made it outstanding in rough field duty. The MR-8 Series provides more elaborate equipment for compositing magnetic records in the field or at an office location. A two-drum system, it has one bank of movable heads to permit the insertion of static corrections. Sequentially-recorded records can be composited 24 channels at a time. In the office location, field records can be processed with 12 channel compositing.

The MR-4 and MR-8 are only two of the SIE magnetic recording systems available for every application in the field or office. Today, more than 60 complete SIE magnetic systems are in operation and have established the Standard of the Industry in magnetic instrumentation.

SOUTHWESTERN INDUSTRIAL ELECTRONICS COMPANY

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SIE

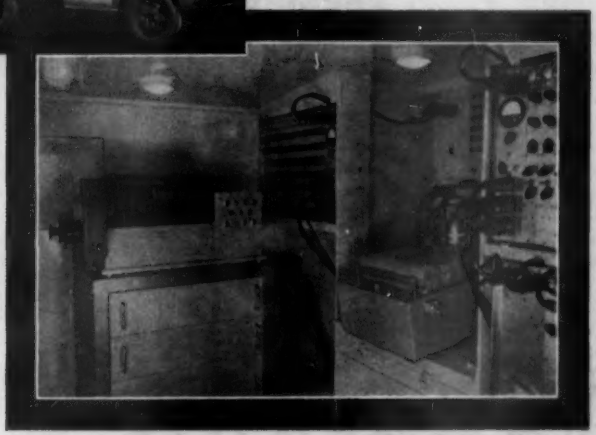
Recognizing that delays in interpretation can sometimes be costly, Petty offers a time saving answer with the "Mobile Vari-Plotter," an on-the-scene data processing laboratory contained in the field recording truck. This magnetic recording unit is capable of quickly producing fully corrected record sections at the site of Petty exploration parties anywhere in the world.

For Today's Exploration

THE FASTEST THING ON WHEELS

Right inside this recording truck, corrections for weathering, elevation and step-out are all applied, and records are timed to a common datum reference in just a matter of hours. Because the "Mobile Vari-Plotter" eliminates the need for central office record processing, your exploration dollar goes farther when using this new Petty service.

Again, Petty's personnel, equipment, methods and experience have teamed up to give you more advanced, economical and rapid exploration service. Put it to profitable use . . . today. Phone, write or call the nearest Petty office.



"Mobile Vari-Plotter" truck carries magnetic recording and complete data processing equipment

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GEOPHYSICAL ENGINEERING CO.
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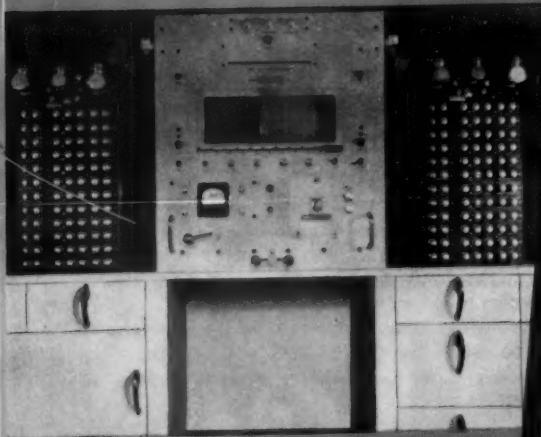
TEXAS DIVISION

THE BRUSH MAGNETIC RECORDING SYSTEM



Model TR-2 Magnetic Recorder-Monitor

THE BRUSH TWENTY-FOUR CHANNEL RECORDER, FOR TRUCK OR BOAT MOUNTING, CONSISTS OF:

MODEL TR-2 MAGNETIC RECORDER-MONITOR

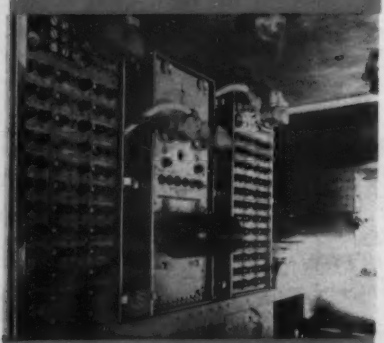
- Twenty-eight channel tape-on-drum recorder.
- Galvanometer style viewing monitor system — for monitoring before and during shooting.
- Direct writing permanent record monitor system, with built-in seismic filters.
- 100 cps timing signal channel.
- Noise cancellation channel (optional use).
- Two information channels (up-hole, time break).
- Twenty-four signal channels.
- Speed lock system for high positional stability.
- New rigid belt drive system for tight, smooth tape movement.

Brush offers a choice of two Amplifier Modulator systems: The Model AM-2 combination Amplifier-Modulators and the Model 721 Seismic Amplifiers with separate Modulator Units. Also, the Recorder and Modulators can be used with any good broad band seismic amplifiers which you may now have available.

MODEL AM-2 AMPLIFIER—MODULATOR UNITS AND CONTROL PANEL

- Twenty-four channels of combined broad band seismic amplifier and frequency modulator.
- Variable soft filtering, for eliminating excessive ground roll or high frequency disturbance.
- Standard high quality seismic amplifier gain, AGC, suppression, line balance, and test features.
- Standard high quality seismic amplifier control panel with trip, suppression control, by-passed first breaks, and test features.

MODEL 521 DUAL PURPOSE SEISMOGRAPH SYSTEM



SUMMARY SPECIFICATIONS

The Model 521 Dual Purpose Seismograph System, consisting of one or two banks of twelve amplifier channels with one control panel each, and of one recording oscillograph, was designed for all types of geophysical operations. Emphasis was placed on ruggedness, long life with minimum maintenance, compactness, and portability. No individual package weighs more than fifty pounds. These units can be used in a light weight recording cab, on truck or boat, and then quickly dismounted for carrying by man.

In addition to the above, main features of the amplifier bank of twelve channels and one control panel are:

1. Fifty pounds weight.
2. 18½" height x 8½" width x 8" depth.
3. Power requirements—16 amps at 6 volts, 27 ma at 90 volts.
4. Input panel, test oscillator, and meter as part of unit.
5. Three selections of mixing.
6. Delay of mixing until after first breaks.
7. Trip on first, sixth, or twelfth trace.
8. Suppression decay.
9. AGC speed of 0.1 second or less, if desired.
10. Non-corrosive, completely water-tight, stainless steel case.
11. Unitized plug-in design to facilitate easy service or replacement.

Main features of the recording oscillograph (six inch, 25 trace recommended for highest degree of portability) are:

1. Thirty pounds weight.
2. 18½" height x 8½" width x 8" depth.
3. Power requirements—Standby— 7 amps at 6 volts.
   Operation—18 amps at 6 volts, 15 ma at 90 volts.
4. Clear visibility of galvanometer spots in daylight.
5. Two hundred feet paper capacity.
6. Record length control.
7. Governor controlled paper speed variable from ten inches to sixteen inches per second.
8. Built-in communication system with two stage amplifier.
9. 100 cps note on 25th trace for hunting check.
10. Non-corrosive, completely water-tight, stainless steel case.

The Recording Oscillographs are available in models handling six-inch to ten-inch paper widths and with six to fifty traces.

WE INVITE YOU TO ASK FOR DEMONSTRATION OF OUR MODEL 521 AND OTHER EQUIPMENT

BRUSH ELECTRONICS

TEXAS DIVISION

MODEL 241
SEISMOMETER BASIC UNIT

MODEL 241 SEISMOMETER BASIC UNIT

The MODEL 241 SEISMOMETER BASIC UNIT is the High Output Basic Unit used in all models of Brush seismometers.

The standard frequencies are 15, 20 and 30 cps. Others may be supplied on special order. The frequency accuracy is held to within one cycle per second.

The matched load voltage sensitivity of a 300 ohm coil is 0.41 volts/inch/sec. The power output of any resistance coil into a matched load is 5.6×10^{-4} watts per $(\text{inch/sec.})^2$.

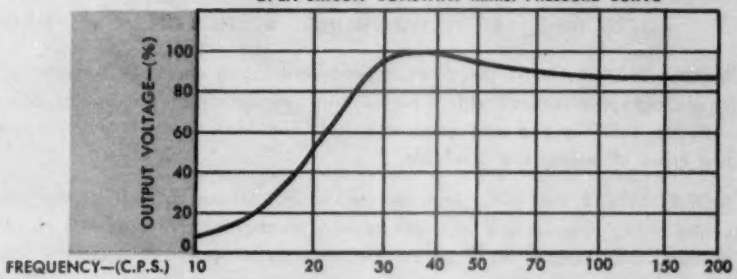
The seismometer is housed in a case machined from solid brass bar stock. The leads are brought out through glass bead hermetic seals.

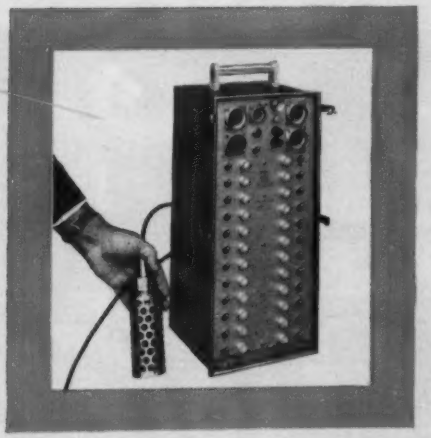
MODEL 321-MT PRESSURE DETECTOR

2½" x 6" • 3 lbs. in Air • 2¼ lbs. in Water

Operating Principle ..... Piezoelectric ceramic with matching transformer.
Ruggedness ..... Will survive at least 20 7-ft. drops to concrete floor and at least 200 lb./in.² pressure.
Sensitivity ..... 0.4 volts/atmosphere—0.4 microvolts/dyne/cm².
Frequency ..... Natural resonance of 22 cps.
Damping ..... No load —50% critical.
300 ohm load—70% critical.
Impedance ..... 300 ohms output impedance at 30 cps.
Recommended Depth of Water ..... Without Preamplifier —25 feet or more.
With Model 700 Preamplifier— 2 feet or more.

OPEN-CIRCUIT CONSTANT R.M.S. PRESSURE CURVE



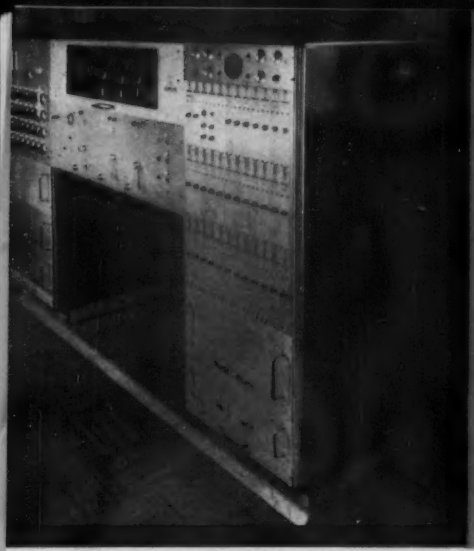


MODEL 700 SERIES PREAMPLIFIER

12 Channel	24 Channel
18½" x 8½" x 5"	18½" x 8½" x 8"
22 Pounds	32 Pounds

Voltage Amplification .. 35.
Power Amplification .... 2,000.
Filtering ..... Approx. 6 db/octave cut beyond 30 cps to offset normal high frequency emphasis of seismic signals in shallow water.
Input Impedance ..... Designed to accept one or more Model 321-MT 300 ohm pressure detectors.
Output Impedance ..... 180 ohms with level control at maximum.
Noise (Electrical) ..... The noise developed with a 300 ohm resistive input (in a band width whose 50% points are 21 cps and 45 cps with a 24 db/octave low cut slope and a 12 db/octave high cut slope) is less than 0.04 microvolt r.m.s. referred to the input. This is approximately 12 db above thermal noise.
Sensitivity ..... Of Model 321-MT 300 ohm Detector and Model 700 Preamplifier is approximately 14 microvolts/dyne/cm².

BRUSH ELECTRONICS
TEXAS DIVISION



MAGNETIC RECORD ANALYZER

MODEL MRA-1 MAGNETIC RECORD ANALYZER — for fixed correction, compositing and reproducing.

THE BRUSH MAGNETIC RECORD ANALYZER for central laboratory or field office use provides, for its end product, the visual photographic record of one or many field tapes — with these flexible features:

CORRECTING • COMPOSITING • FILTERING • MIXING

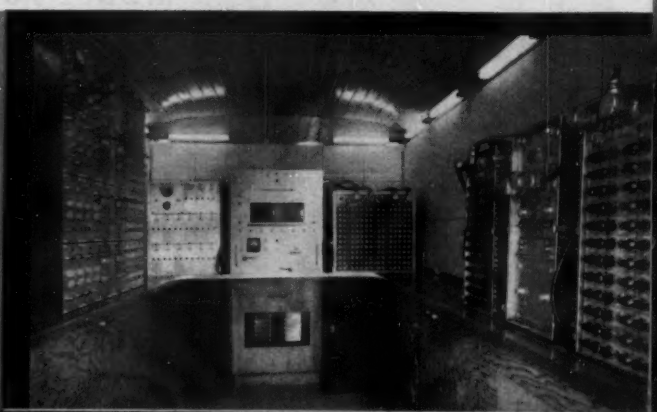
The MODEL MRA-1 inserts the constant weathering and elevation corrections. It provides time section photographic records with these constant corrections. It composites any number of tapes shot with the same spread and same shot hole (different depths). A broad selection of filtering and two types of mixing are available.

The MODEL MRA-2 inserts the variable stepout corrections as well as the constant corrections. It provides either time section or depth section photographic records with all corrections inserted. It composites any number of tapes shot with the same spread and different shot hole locations and depths. A broad selection of filtering and two types of mixing are available.

DEMONSTRATION UNIT — Now on tour

Contains Magnetic Recording as well as conventional equipment.

Please inquire as to date on which Demonstration Unit will be in your area.



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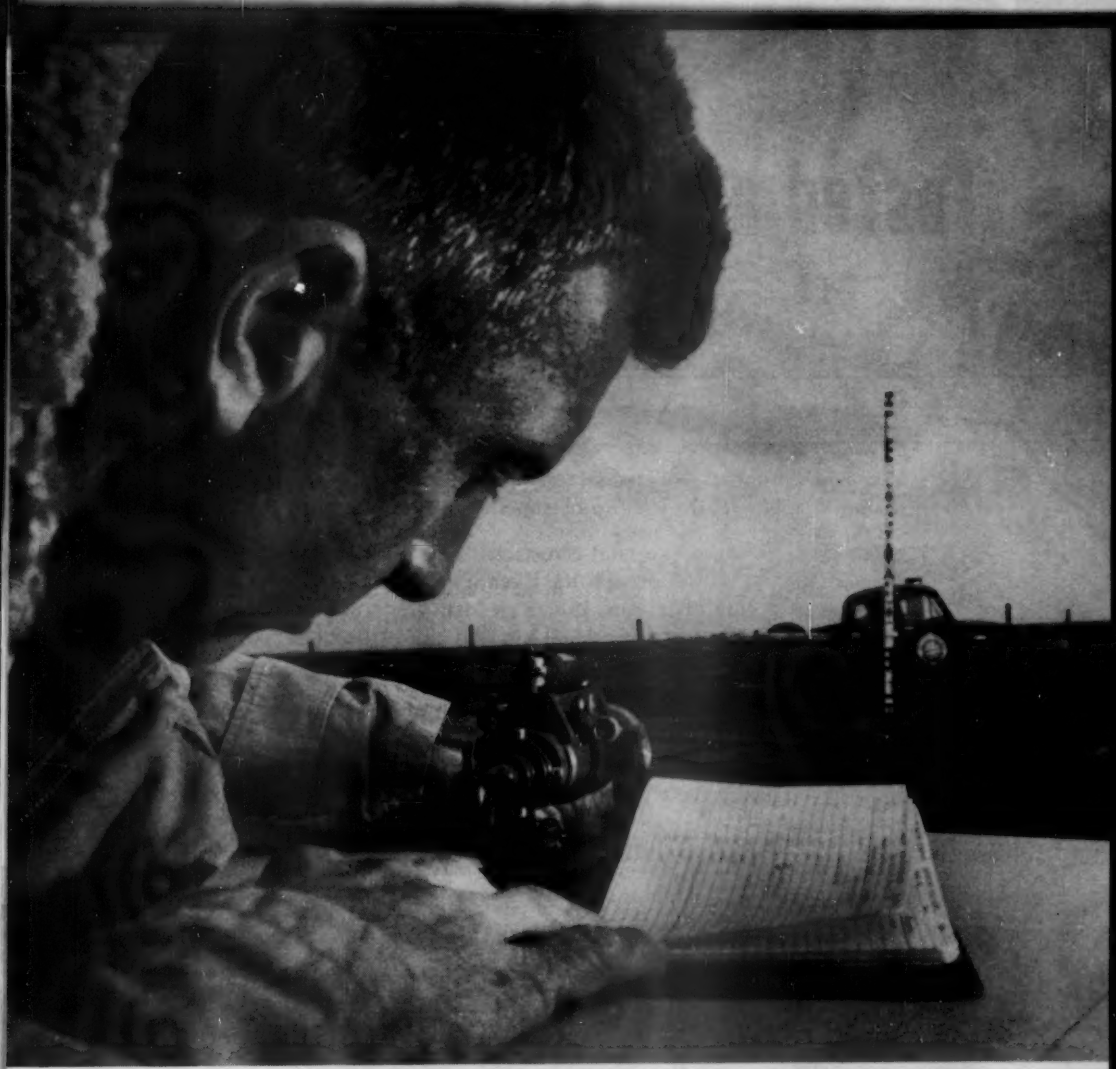

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SPEED is increased in two vital directions: Seismo-Writ is faster in exposure *and* quicker in processing. Even if extreme underexposure forces overdevelopment, your shot isn't lost. You still get a good, clear, easy-to-read record. And Seismo-Writ can be processed with developer temperature well above 100 degrees F.

STABILITY. Seismo-Writ has minimum curl and won't crack. It's easy to handle, roll, or store—because it's a tough paper designed for every punishing field condition. Furthermore, Seismo-Writ doesn't soften, even under the worst conditions of heat and development.

CLARITY. Seismo-Writ offers freedom from stain and fog, which makes interpretation easy. You get good readable density both in timing lines and reflection traces.

CONVENIENCE. Waterproof package doubles as self-mailer, with space for address and postage. Seismo-Writ is packed in a waterproof, heat-sealed moisture-proof package, assuring safe storage of the paper *before* it's used, and it guards your records *after* the shot is made.

What else should you know about improved Seismo-Writ? Send in the coupon below for a free booklet with all the facts.

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- What tape to use for long or short wave length recording

SCOTCH BRAND Magnetic Tapes

INSTRUMENTATION DIVISION

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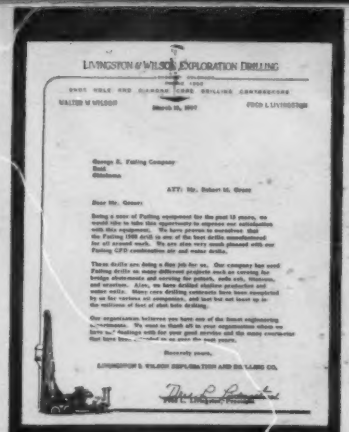

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ATT: Mr. Robert M. Grant

Dear Mr. Grant:

Being a user of Failing equipment for the past 13 years, we would like to take this opportunity to express our satisfaction with this equipment. We have proved to ourselves that the Failing 1500 drill is one of the best drills manufactured for all around work. We are also very much pleased with our Failing CFD combination air and water drills.

These drills are doing a fine job for us. Our company has used Failing drills on many different projects such as coring for bridge abutments and coring for potash, soda ash, titanium, and uranium. Also, we have drilled shallow production and water wells. Many core drilling contracts have been completed by us for various oil companies, and last but not least up in the millions of feet of shot hole drilling.

Our organization believes you have one of the finest engineering departments. We want to thank all in your organization which we have had dealings with for your good services and the many courtesies that have been extended to us over the past years.

Sincerely yours,

LIVINGSTON & WILSON EXPLORATION AND DRILLING CO.

Fred L. Livingston, President

Thank you, Mr. Livingston...

for praising the many ways Failing Rigs serve you; such as your record of

"MILLIONS OF FEET OF SHOT HOLE DRILLING"

In his letter, Mr. Fred L. Livingston, President of Livingston & Wilson Exploration Drilling of Longmont, Colorado, tells of the wide use they've given to their Failing Equipment during the past 13 years.

Mr. Livingston states, "We have proved to ourselves that the Failing 1500 drill is one of the best drills manufactured for all around work. We are also very much pleased with our Failing CFD combination air and water drills.

"Our company has used Failing drills on many different projects such as coring for bridge abutments and coring for potash, soda ash, titanium and uranium. Also . . . shallow production and water wells. Many core drilling contracts have been completed by us for various oil companies, and, last but not least, **up in the millions of feet of shot hole drilling.**

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Filbert stared blankly into space. A dull film clouded his eyes. Surely, with luck, he would be dead in five minutes. But visions of his widowed wife and fatherless children pulled him to his feet and sent him trudging out the door . . to the library.

It would take all day. He'd be spending valuable time his company could hardly afford. And he'd be using all his exploration skill to locate that blessed paper — not to mention structures . . . Filbert stopped at a drug store and bought $4.00 worth of aspirin.

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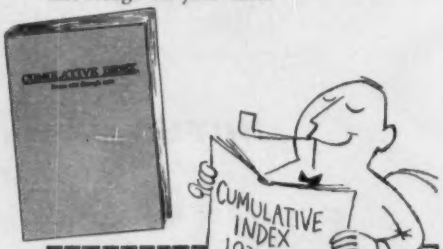

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More on the Gravity Terrain Problem

Last time (*Geophysics*, Volume XXII, Number 2, page 82), we suggested a method which took the guess work out of making terrain corrections. This involved using a *Terrain Transit* for the inner zone, and topographic maps for the outer zones.

No doubt many of our readers have been busy, with a topographic map and grid at one elbow, and a desk calculator at the other, computing these outer terrain effects. They are probably as tired as the rodman who climbed all those hills. We have relief for the computer too.

Again we resort to those new labor saving machines that take the mathematician away from the drudgery of his "hot desk calculator." Using electronic digital equipment, we calculate the terrain effect of the outer zones and prepare a contoured map of the results.

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A NEW LOOK

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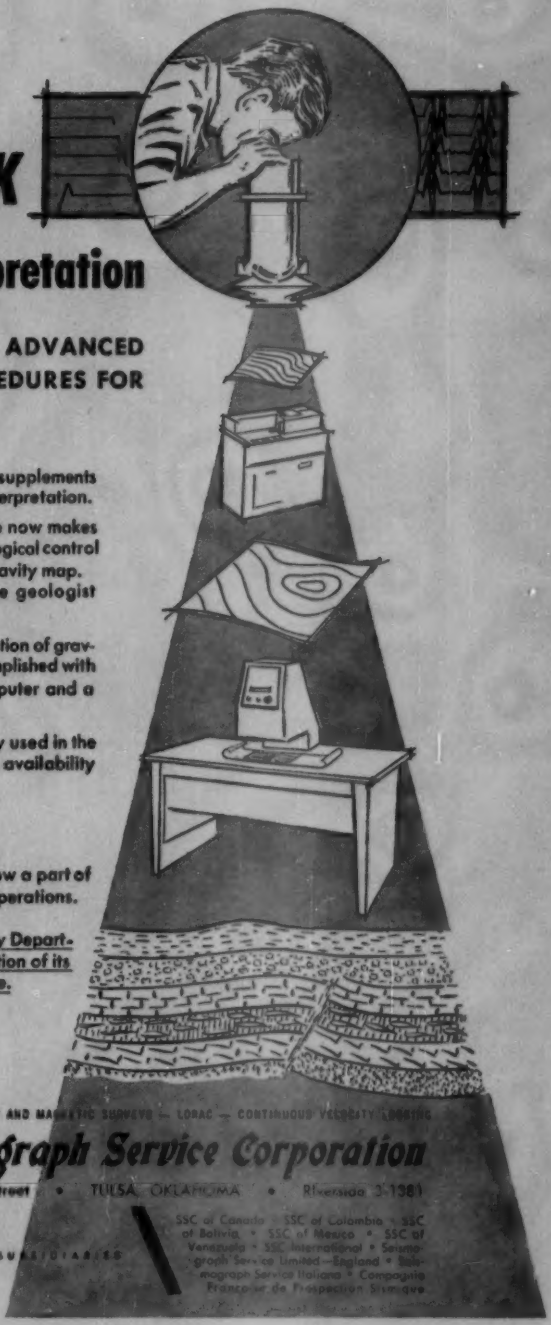

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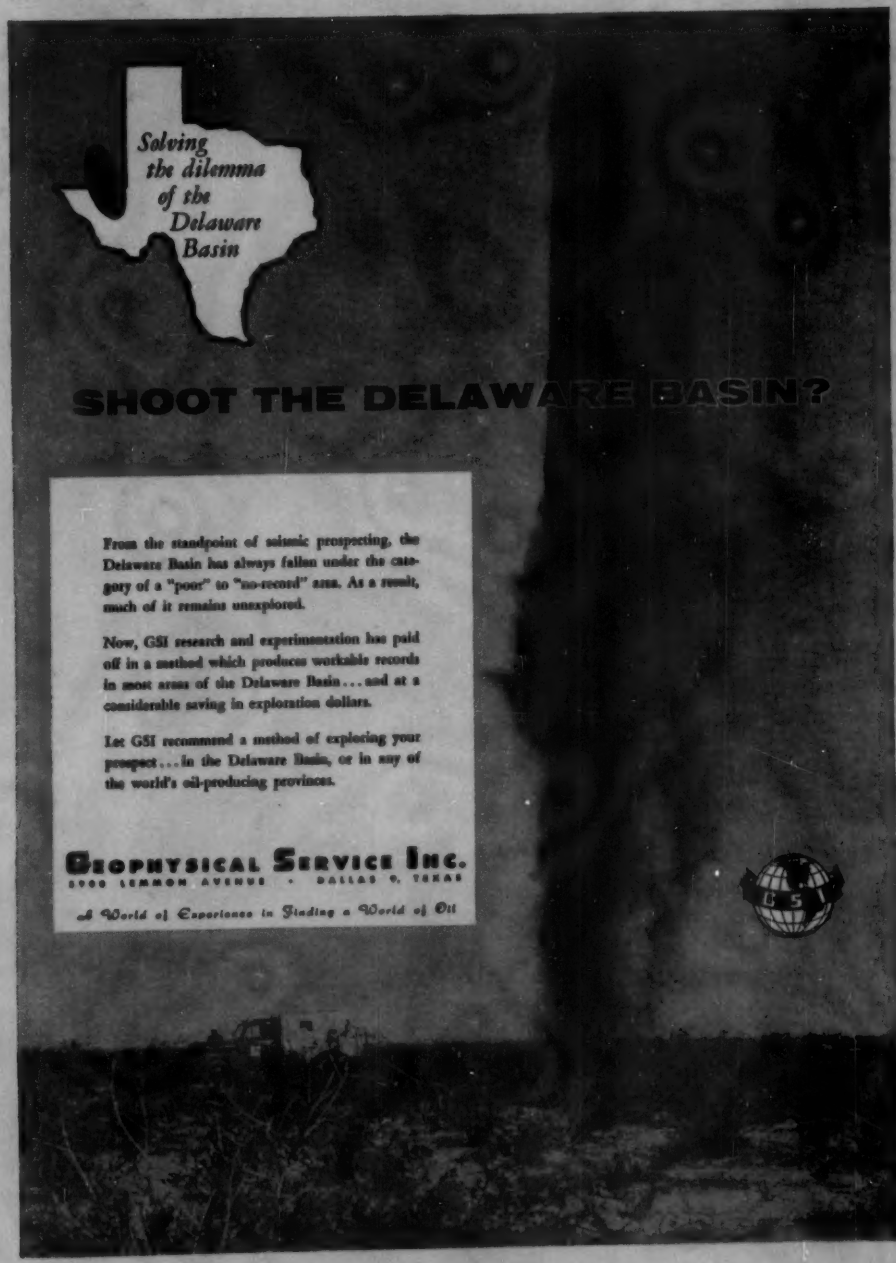
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